Corrosion of Welded Metal Structures of Mining Equipment

DAN DOBROTA*
Lucian Blaga University of Sibiu, Faculty of Engineering, 10 Victoriei Blvd., 550024, Sibiu, Romania

Mining equipment made of welded metal structures is strongly affected by the corrosion phenomenon due to the working conditions. Initial research has shown that the corrosion phenomenon is most pronounced in the area of cross-welded joints and welded T-shaped joints. In the researches, there was made a chemical analysis of the welded construction material used respectively of the new material and it was observed a reduction in carbon concentration in the material used, but also a substantial increase in the sulfur concentration compared to the new material. The pronounced corrosion of the metallic structure is influenced by the chemical composition change because the sulfur is a grafitizing and weakening element, and the decrease in carbon concentration causes a decrease in corrosion resistance. Also, the pronounced corrosion is due to the action of sulfurous acid (H_2SO_3) and hydrogen sulfide (H_2S), elements that are present in the working environment of welded constructions. In order to achieve a reduction in the corrosion phenomenon, it is very important that the welded joints are made using the optimal parameters of the welding regime so as to obtain metallographic structure with finer granulations.

keywords: corrosion, mining equipment; corrosion, hydrogen sulphide, sulfuric acid

Welded constructions of mining equipment are made of low alloyed steels with good weldability. Such constructions have to be carried out under certain conditions in order to provide a high resistance to fatigue and corrosion under the present varying loads and environmental conditions outstanding. The presence of a cracking phenomenon caused by fatigue and certain environmental conditions may result in the degradation of large-scale equipment used in surface mining. Under these conditions, it is very important to analyze the presence of fatigue cracking phenomenon under conditions of low mechanical stress, but in the presence of a strong corrosive environment, as in the case of open cast mines [1].

Researche done in the case of low-alloy steels, under laboratory conditions, has shown that fatigue crack growth rates are faster in dry gaseous media (argon, hydrogen and air) than in wet air. Under these conditions it was observed that the environments in which the mining equipment works are favorable to the rapid increases in fatigue cracks. Also, under laboratory conditions, it has been demonstrated that an increase in the mechanical strength of materials causes an increase in the fatigue crack growth rate in different environments [2-4].

An important property of materials that influence the fatigue behavior of low-alloy steels is ductility. Thus, it has been shown that the ductility of low alloyed steels depends significantly on the orientation of the stressing system, but also on the triaxial nature of the stress condition [5].

Also, the metallographic studies performed in the case of low alloyed steels have demonstrated that the size, shape and orientation of the crystalline grains influence at the fatigue and corrosion behavior. Thus, the application of ductile fracture models to low alloyed steels has demonstrated that a particular influence on fatigue behavior has the direction of orientation of the crystalline grains relative to the direction of stress.

Under these conditions, the influence of the size of the crystalline grain is very important on the fatigue behavior of the metal structures and the appearance of the cracking phenomenon through corrosion [5].

It is known that reducing the size of the metallographic grains leads to improved mechanical strength, wear resistance and corrosion resistance of a low alloy steel [6, 7]. By reducing of the size of graines, both the volume and the shape of the material surface is change, resulting in changes in the limit density of the metallographic grains, the orientation and the residual stresses. Changes in the shape of the surface of the materials may have an impact on electrochemical behavior and therefore on corrosion susceptibility, as evidenced by the large number of studies of the granule size effect on the corrosion, which covering a large range of test materials and environments [8, 9]. However, there are still limited studies on the development of a fundamental understanding of how the size of a metallographic grain affects the corrosion resistance of a steel. The results of experimental research are often contradictory, even within the same alloy class, and a coherent understanding of how the crystalline grain dimension influences the corrosion resistance of materials is largely absent. An analysis of the research on the relationship between granule size and resistance to corrosion for a number of light metals (Mg, Al and Ti) and transition metals (Fe / Steel, Co, Ni, Cu and Zn) has made it possible to identify a number of critical factors such as the environment, texture, rezidual stress, the segregation of impurities to be considered to assess whether and how the variation in the size of the crystalline grains can affects the electrochemical behavior of a specific alloy in a given environment [10-13].

Metallic structures of mining equipment operate at temperatures between - 30 ^{0}C ÷ + 40 ^{0}C. Thus, certain conditions are created for the occurrence of the creep phenomenon. In these circumstances, the results are useful for determining, for example, the load capacity of a structure under fire conditions and predicting regarding the length of its life.

The chemical composition of low-alloy steels influences their welding behavior [14]. Thus, the best mechanical properties of welded joints were obtained for two steels having 1.92 % Mn and 0.02 % Ti respectively 1.40 % Mn si 0.08 % Ti. For these types of steels, an increase in the proportion of acicular ferrite in the microstructure was achieved by the addition of titanium in the range of 0.02 - 0.08 %. Also by adding mangan to the chemical composition, they was obtained refining and homogenization of the microstructure of the welding seams. The increase in welding capacity is due to the

* email: dan.dobrota@ulbsibiu.ro; Tel. +400722446082

addition of titanium or manganese, and this has determined a bainitic structure with a higher frequency than a metallographic structure made of acicular ferrite. Also, the amount of manganese in inclusions decreased by adding titanium to the weld. The impact resistance of the welded structure may increase if the chemical composition has been improved by the addition of titanium, but also under these conditions the tendency of cracking does not completely disappear [15].

Increasing the service life of welded constructions in coal mining quarries is possible through constructive improvements or optimization of the welding process parameters used in the execution stage as well as in interventions and repairs. In the design stage of welded constructions, constructive and technological solutions must be adopted to eliminate and prevent non-conformities in operation. Analyzes performed have shown that the most dangerous defect that can occur in welded constructions of coal mining machinery is fragile tearing. An important factor that can cause fragile breaking phenomena is the temperature at which technological welding processes and the presence of corrosion occur [16, 17].

Thus, the execution temperature generates conditions for certain degradation modes by breaking the low alloyed steels used for the execution of the welded constructions of the equipment in the quarries for coal exploitation [18].

Also, the execution temperature generates conditions for certain degradation modes by breaking the low alloyed steels used for the execution of the welded constructions of the equipment in the quarries for coal exploitation. In order to prevent fracturing weakly alloyed steels, they must be deoxidized with silicon, aluminum and titanium, and the welding process should be done at a temperature above 10 °C to avoid embrittlement in the heat-affected zone [19, 20].

The operating temperature greatly influences the way in which the degradation of the welded construction occurs. Thus, the fragile breaking of the welded structure can also occur if the thickness of the welded elements is greater than 25 - 30 mm, if the thermal stresses are more intense. At the same time, in order to avoid the fragile breaking of the welded structure, it is necessary to preheat the elements subjected to the welding joint and the pre-heating temperature is chosen depending on the operating temperature of the welded parts and the thickness of the welded parts [21].

Experimental part

Materials and methods

For machines in the lignite open pit mines, the most requested part is the welded metal construction, in which most of the defects have occurred, due to technology and material nonconformities. Any deficiency in the execution of the welded structure leads to an increase the stresses in its material, and this inevitably leads to a decrease in the predicted lifetime. The analysis of the welded construction of the equipment from the open pit mines of the lignite, highlighted the following types of degradation were found [22]:

- degradations during the warranty period (1.5 - 3 years) due to subjective causes, from which we mention the design ones (constructive solutions, materials, welding details etc.), and exploitation (repeated overloading);
- degradations occurring after 5 - 7 years of operation, which generally have causes related to how the machine operated in special operating regimes in heavily corrosive environments over long periods of time. In the case of equipment of quarries, geological conditions, environmental conditions and non-compliance with planned repair schedules in the mechanisms are causes that cause degradation on the welded construction.

In the case of mining equipment, the complex loads due to the excavation of tailings and coal with speeds, positions and intensities varying over time, in the welded structure elements require that elements welded structures have provided some resistance to fatigue and corrosion.

Among the factors that influence the corrosion behavior of welded structures, the quality of the base and addition materials as well as the technology of welded joints are of decisive role. The small discontinuities in welded joints, including corroded dots, surface scratches, polishing grooves, cracks and welding defects (porosity, notches, cracks, slag inclusions, lack of penetration and fusion) generally determines the exact positioning of the zone corrosion the appearance of corrosion. Over the past two decades, a rather large number of local defects could be observed in some elements of welded constructions. Due to corrosion propagation in the material structure, in many cases, it appeared fragile ruptures. Most cracks resulted from the phenomena of corrosion cracking, which is mainly located in the zone of the welding seam.

In the event of a crack caused by the phenomenon of corrosion cracking, almost simultaneously a large number of microcracks are triggered in the structure, and in a relatively short time there may be a catastrophic cracking of the welded structure. Generally, cracks are developed in parallel planes of operating stresses and do not jeopardize the weld structure if they are discovered in time before crack propagation is perpendicular to direction of the effort and cause the breakage. The choice of metallic, base and joining materials for the achievement of a steel construction of a mining equipment is an important problem with a high degree of complexity. By optim choosing metal materials, must ensure of the construction efficiency as high in terms of execution (production, assembly), exploitation (safety in operation, maintenance), steel consumption and cost. The realization of durable metal constructions with a good operating behavior is determined by the preservation of the tenacity of welded joints and welding seams. The tenacity of welded joints is a factor closely related to the notion of weldability. The weldability of the steels depends on many factors and it is a complex feature that determines the weldability of the steels under certain welding conditions, the technical ability of the steels to achieve certain joints [23].

In recent years, at welded steel constructions realised of thick steel plates appeared defects due to the reduced mechanical characteristics of the plates, perpendicular to the thickness direction.

Steel manufacturers are looking to investigate metallurgical problems, conditioned by the quality of the materials, trying to obtain steel sheets with ensuring technical properties. At the same time, designers seek to limit the demands in the direction of thickness through constructive measures, which also cover the execution technology.

For example, the frequency of lamellar cracks in the steel sheet increases as the preheat temperature decreases and the sulfur and hydrogen content increases. It seems that there is no dependence between the crack frequency and the thickness of the steel sheet, and these appear on thin, 10 and 12 mm sheets.

The analysis of a welded construction, (fig. 1), led to the following conclusions:

- crackings occur due to the fact that the material becomes unstable in the heat affected zone, but also due to the occurrence of the phenomenon of craking corrosion;
- welded constructions have a good exploatation behavior if they are made of a steel with optimal weldability characteristics;

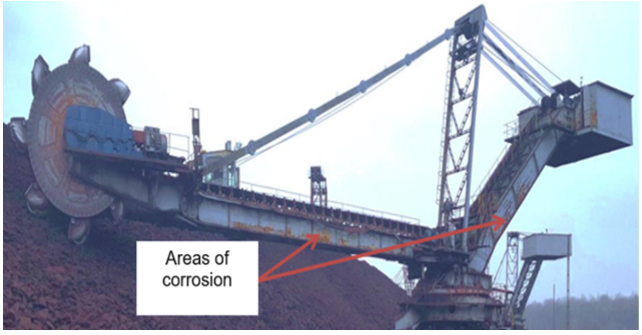

Fig. 1. General view of a machine for extracting coal with corrosion areas the metal structure

- welded joints must be made with the choice of an optimal welding process, but also with the setting of optimal welding parameters;
- it is necessary to adopt appropriate construction systems, to avoid the presence of concentrators of tension and sudden changes of section;
- developing new qualities of weldable, calming, with fine-grained steels, limiting carbon content to maximum 0.22 % and manganese between 0.75 - 1.70 %.

From the analysis of the metal construction of the equipment used in the open pit mines (fig. 1), it was noticed that most of the problems related to the behavior in operation occur in the case of welded corner joints in T, (fig. 2), respectively in the case of a cross-shaped welded joints, (fig. 3). This situation can be explained by the fact that during the realization of the welded construction the optimal parameters of the welding process were not established. Also, these constructive forms of welded joints are mostly subject to an intense process of cracking corrosion, which occurs in a relatively short time. This is explained by the fact that such structural forms allow the accumulation on their surface of large amounts of corrosive agents (coald dust, earth, waste water). Thus, the main objective of the research was to find the right technological solutions for obtaining such welded joints with the highest corrosion resistance.


Fig. 2. Welded corner joint in T shape


Fig. 3. Welded joint in the cross shape

Results and discussions

In order to identify causes that cause the increased corrosion of welded joints, a chemical analysis of welded material on the used equipment and the new material was also carried out. Determination of chemical composition was performed using a NITON XL3t portable X-ray fluorescence (FRX) portable spectrometer, and results are shown in Table 1 for new material, low alloyed steel S355JR, and for material on the machine (table 2).

From the analysis of the data presented in table 1 and table 2, there was observed a reduction in carbon concentration in the material used, but also a substantial increase in sulfur concentration. The increase of the sulfur concentration is explained by the fact that in the working environment of the mining equipment there are large quantities of SO_2 and its presence causes the occurrence of compounds of the type:

- sulphurous acid (H_2SO_3) which is formed when the air polluted with sulfur dioxide also has a high moisture content or water droplets, the chemical reaction being the following:

$$SO_2 + H_2O \rightarrow H_2SO_3$$

- hydrogen sulfide (H_2S)

$$SO_2 + 3H_2 \rightarrow H_2S + 2H_2O$$

The corrosion that occurs in the case of the presence of the two types of compounds is a complex phenomenon. Thus, hydrogen sulfide which is a weak acid and if it is dissolved in water acts as a catalyst in the absorption of hydrogen atoms in steel, and this creates conditions for the fragility of the steel structure and the acceleration of the corrosion process. Also cracks due to hydrogen inclusions concentrated in areas with strong stresses make the steel very fragile. Thus, the steels specific to metal construction of the mining equipment show the corrosion caused by the internal stresses in the material.

In the environments with hydrogen sulphide and sulphurous acid the most common types of corrosion encountered are:
- uniform corrosion;
- spot corrosion;
- fatigue corrosion;
- corrosion caused by stresses.

From the analysis of the surfaces of the metal structures of the mining equipment, it was observed that on their surface there is a corrosion in points, observing also a series of corrosion craters (fig. 4).


Fig. 4. Corrosion of metal construction under the action of sulphurous acid (H_2SO_3) and hydrogen sulfide (H_2S)

Presence in the environment of sulphurous acid (H_2SO_3) and hydrogen sulfide (H_2S) determine a great corrosion of the steel in metal construction of the mining equipment, and Fe from steel reacts with the two chemical compounds:

$$Fe + H_2S \rightarrow FeS + H_2$$
$$2Fe + 6(H_2SO_3) \rightarrow Fe_2(SO_4)_3 + 6H_2 + 3SO_2$$

Presence of sulphurous acid (H_2SO_3) and hydrogen sulfide (H_2S) in the environment in which mining equipment is working is mainly explained by the fact that all coal-mining quarries are located near the thermal power stations that emit into the atmosphere, after the coal-firing, large amounts of SO_2. Although in recent years gas desulphurisation installations have been carried out in the process of coal combustion, however, a fairly large amount reaches the atmosphere, making the environment strong corrosive.

Table 1
CHEMICAL COMPOSITION OF NEW MATERIAL

C %	Mn %	Si %	S %	P %	Al %
0.217	1.658	0.053	0.025	0.021	0.011

Table 2
CHEMICAL COMPOSITION OF THE USED MATERIAL

C %	Mn %	Si %	S %	P %	Al %
0.183	1.260	0.049	0.057	0.021	0.010

Also, from the researches carried out, it was observed that the increased corrosion occurs in the area of welded T or crossed joints. This demonstrates that dust arising from coal exploitation is a carrier of sulfur components, and so with humidity in the atmosphere it generates compounds with strong corrosive action.

Also from the chemical analysis was a reduction in the concentration of the alloying elements (Mn, Si) in the case of the steel used with respect to the new steel, which results in a decrease in the presence of carbides in the steel which gives it a high corrosion resistance.

Also, this is explained by the fact that some of the carbon separates over time and diffuses outwards or forms new structural constituents, and the increase in sulfur concentration is explained by its diffusion from the environment is one characterized by large amounts of sulfur and especially hydrogen H_2S sulfide. Thus, a reduction in carbon content results in a decrease in breaking strength and material hardness, which causes the reduce of welded construction capacity to take on different external loads. Increasing the sulfur content leads to strong segregation, making the materials brittle. Also, the presence of sulfur in large quantities can cause segregation of carbon to form graphite nests, and this is also explained by the fact that sulfur is a strongly grafitizing chemical element. Also from the analysis of the chemical composition results it is observed that in the material used there are decreases in the concentration for most of the alloying elements, and this can lead to a reduction of the mechanical and exploitation characteristics of the material used.

Conclusions

From the analysis of the results obtained in the research I found the following:

- welded constructions of technological equipment in mining installations are strongly corroded, appearing a complex phenomenon of corrosion;
- the material of welded constructions of mining equipment suffers, after a certain period of use, structural changes and chemical composition, which may also lead to a reduction in its mechanical characteristics;
- the corrosive phenomenon is mainly due to the aggressive working environment in which these equipment is used (the presence of sulfur in the atmosphere and the formation of H_2S - hydrogen sulfide, H_2SO_3 - sulfuros acid);
- the cracking corrosion phenomena appear particularly in the area of T - shaped welded joints in the cross-section of the welded constructions and in this respect it is recommended to adopt constructive modifications so as to avoid such types of joints;
- to reduce the corrosion phenomenon, it is necessary to take anticorrosive protection measures of the metallic surfaces by applying protective layers with high resistance to environment.

References

1.DUDZINSKI, W., KONAT, L., PEKALSKI, G. Modern constructional steels. In Maintenance Strategy of Surface Mining Machines and Facilities with High Degree of Technical Degradation; Dudek, D., Ed.; Publishing House of Wroclaw University of Technology: Wroclaw, Poland, 2013, p. 346–366.

2.BORDBAR, S., ALIZADEH, M., HASHEMI, S.H. Effects of microstructure alteration on corrosion behavior of welded joint in API X70 pipeline steel, Mater. Des., No. 45, 2013, p. 597–604.

3.DOBROTA, D., AMZA, Gh. Ultrasound effect on the mechanical properties of parts loaded by welding, Metalurgija, 52, No. 1, 2013, p. 83-86.

4.MORTEZAIE, A., SHAMANIAN, M. An assessment of microstructure, mechanical properties and corrosion resistance of dissimilar welds between Inconel 718 and 310S austenitic stainless steel, International Journal of Pressure Vessels and Piping, No. 116, 2014, p. 37-46.

5.WANG, Y.Y., KANNAN, R., LI, L.J. Characterization of as-welded microstructure of heat-affected zone in modified 9Cr–1Mo–V–Nb steel weldment, Mater. Charact, No. 118, pp. 225–234.

6.SABZI, M., OBEYDAVI, A., MOUSAVI ANIJDAN, S.H. The effect of joint shape geometry on the microstructural evolution, fracture toughness, and corrosion behavior of the welded joints of a Hadfield Steel, Mechanics of Advanced Materials and Structures, 2018, https://doi.org/10.1080/15376494.2018.1430268

7.SERAFIM, A., OLARET, E., CECOLTAN, S., BUTAC L.M., BALANUCA, B., VASILE5, E., GHICA M., STANCU I.C., Bicomponent Hydrogels Based on Methacryloyl Derivatives of Gelatin and Mucin with Potential Wound Dressing Applications, Mat. Plast., **55**, no. 1, 2018, p. 68-74.

8.UNNIKRISHNAN, R., SATISHiDURY K.S.N., ISMAIL T.P., BHADAURIA A.; SHEKHAWAT S.K.; KHATIRKAR, R.K., SANJAY SAPATE, S.G. Effect of heat input on the microstructure, residual stresses and corrosion resistance of 304L austenitic stainless steel weldments, Materials Characterization, No. 93, 2014, p. 10-23.

9.ZHAO, W., ZOU, Y., MATSUDA, K., ZOU, Z.D. Corrosion behaviour of reheated CGHAZ of X80 pipeline steel in H_2S - containing environments. Mater. Des., No. 99, 2016, p. 44–56.

10.MIRSHEKARI, G.R., TAVAKOLI, E., ATAPOUR M., SADEGHIAN B. Microstructure and corrosion behavior of multipass gas tungsten arc welded 304L stainless steel, Materials & Design, No. 35, 2014, p. 905-911.

11.SZOTA, M., LUKASZEWICZ A, Corrosion resistance of injection-casting dental implants, Rev. Chim. (Bucharest), **69**, no. 8, 2018, p. 2183-2186.

12.E.J., VAN TYNE, C.J. Correlation of Yield Strength and Tensile Strength with Hardness for Steels. J. Mater. Eng. Perform, No. 17,2008, p. 888-893.

13.DINU, A., RADU, V., Chloride Stress Corrosion Cracking of Incoloy -800, Rev. Chim. (Bucharest), **65**, no. 7, 2014, p. 822-827.

14.IORDACHE, D.M., DUCU M.C., NITU E.L., IACOMI, D., PLAIASU A.G., PASARE, M.M., Microstructure and Properties of Copper and 5754 Aluminum Alloy Joints by Friction Stir Welding, Rev. Chim.(Bucharest), **68**, no. 3, 2017, p. 459-463.

15.SATHIRACHINDA, N., PETTERSSON, R., PAN, J. Depletion effects at phase boundaries in 2205 duplex stainless steel characterized with SKPFM and TEM/EDS. Corros. Sci., No. 51, 2009, p. 1850–1860.

16.ZHAO, X.; LI, F.; LIU, Y.; FAN, Y. Fatgue behavior of box-type weded structure of hidraulic support used in coal mine, Materials. 2015, 8(10), 6609-6622.

17.BUCUR, G., MOISE, A-G., BUCUR, L. Quantitative analysis method for hydrogen diffusion in chemical equipment welded joints, Rev. Chim.. (Bucharest), **65**, no. 10, 2014, p.1210-1214.

18.JANG, S., KIM, S., LEE, I., PARK, Y. Effect of shielding gas composition on phase transformation and mechanism of pitting corrosion of hyper duplex stainless steel welds. Mater. Trans., No. 52, 2011, p. 1228–1236.

19.LI, H.B., JIANG, Z.H., FENG, H., ZHANG, S.C., LI, L., HAN, P.D. Microstructure, mechanical, and corrosion properties of friction Stir Welded high nitrogen nickel-free austenitic stainless steel. Mater. Des., No. 84, 2015, p. 291–299.

20.RISTON, K.D., BIRBILIS, N., DAVIES, C.H.J. Revealing the relationship between grain size and corrosion rate of metals. Scr. Mater.**,** No. 63, 2010, p. 1201-1204.

21.AMZA, G., DOBROTA, D., GROZA DRAGOMIR, M., PAISE, S., APOSTOLESCU, Z., Research of environmental impact assessment of flame oxyacetylene welding processes, Metalurgija, 52, No. 4, 2013, p. 457-460.

22.SHI, Y., SUN, K., CUI, S., ZENG, M., YI, J., SHEN, X., YI, Y. Microstructure Evolution and Mechanical Properties of Underwater Dry and Local Dry Cavity Welded Joints of 690 MPa Grade High Strength Steel, Materials, No. 11, 2018, p. 167.

23.EGHLIMI, A., SHAMANIAN, M., RAEISSI, K. Effect of current type on microstructure and corrosion resistance of super duplex stainless steel claddings produced by the tungsten arc welding process. Surf. Coat. Technol., No. 244, 2014, p. 45–51.

Manuscript received: 15.02.2018