REAL AND IMAGINARY OBSTACLES OF ALUMINUM ALLOYS APPLICATION IN PETROCHEMICAL INDUSTRY

KONDRAT'EV Sergey, SHVETCOV Oleg

Peter the Great St. Petersburg Polytechnic University, Technology and materials research department, St. Petersburg, Russian Federation, petroprom2013@yandex.ru

Abstract

The study deals with advantages and disadvantages of aluminum alloys application for oil and gas extraction. Aluminum alloy applications in drilling pipes, tapered and casing tubing as well as in raisers to extract hydrocarbons were widely known for a long time. As a result, the limitation and obstacles of aluminum alloys application in the petrochemical industry were brought for reconsideration.

The results of alloying systems Al-Cu-Mg and Al-Zn-Mg-Cu application in real field developments and basic problems related to contact corrosion in corrosive environment and high temperatures were studied. The results were received; the examples verifying 2024 and 1953 aluminum alloys temperature stability in the temperature range of 200 - 250 °C during both short-term within 3 - 10 minutes and long-term operation up to 1000 hours at 150 °C in the well environment were presented. The testing results of pilot micro arc oxidation of surface treatment of near-to-fastener pipe area, current treatment isolated contact between an aluminum pipe and steel joint to avoid negative impact on contact corrosion were provided. These data verified the feasibility of 2024 and 1953 alloy pipes compared to steel pipes. Also, aluminum alloys corrosion stability under the real operation conditions was proved. The obtained results showed the aluminum alloy advantages compared to steel prefabricated pipes, and the provided examples illustrated possible techniques to minimize aluminum alloys drawbacks and eliminate imaginary obstacles for further implementing light alloy pipes in the petrochemical industry.

Keywords: Al-Cu-Mg alloying system, Al-Zn-Mg-Cu alloying system, 2024 and 1953 alloys, drill pipe, mechanical and corrosion properties.

1. INTRODUCTION

Currently, due to exhaustion of the easily extracted resources, i.e. oil and gas, the petrochemical industry has to develop fields in large depth and apply direct or deepwater drilling. Modern drilling technologies are designed to increase the equipment capacity or use of alternative steel materials [1-4]. One of these alternatives can be aluminum alloys, their test application in the oil and gas industry started in 1960. Experience with high-strength aluminum deformed alloys for manufacturing drill pipes proved their significant advantages compared to steel [5]. As the main advantages of aluminum pipes are low density and high specific strength, so the latter has great significance in present-day conditions due to the increase in required development of new deposit fields, located in large depths with potential resources that are extremely difficult for extraction. However, up to now aluminum alloys application was rather limited, and it can be explained by the conservative approach widespread in the oil and gas industry. And the main challenge for its application is the lack of practical guidelines for a manufacturing process and acceptable operating environment for drilling pipes made of aluminum alloys.

Drilling pipes made of aluminum alloys are generally manufactured with steel joints for further assembly in drilling columns in situ, with the help of pipe steel locks which are fit by applying thread shrinkage. As a result of this manufacturing technique lock and pipe material heating occurs. Such a heating may result in a significant change of properties for alloy materials, causing diffusion processes in metals, thus leading to structure and phases transformations. In the process of further exploitation assembled aluminum drill pipes (with steel locks) are exposed to long-term (up to 1000 hours) heating to the temperature of 150 ^{0}C and corrosion environment impact in oil and gas fields. The severe conditions influence significantly the structure and, consequently, aluminum alloys properties as well. However, the influence of the factors mentioned above on the structure and properties of aluminum alloys used to manufacture drilling tools was not researched on a regular basis.

The study is targeted at presenting development and explanation of practical recommendations for service life increase using aluminum alloys in the oil and gas industry based on the research into technological parameters influence of manufacturing and drilling pipe operation conditions on the structure and properties of 2024 and 1953 aluminum alloys.

2. METHODOLOGICAL BASIS

The drilling pipes with the outside diameters of 147 mm and 90 mm of 2024 and 1953 aluminum alloys for Al-Cu-Mg and Al-Zn-Mg-Cu systems were investigated in the initial conditions after standard heat treatment and in field operation. According to standard heat treatment conditions 2024 alloy undergoes quenching at the temperature of 500 °C in water, and natural aging pending amounts for 4 days. According to standard heat treatment conditions 1953 alloy undergoes quenching at the temperature of 480 °C in water, and artificial ageing proceeds during 24 hours with the temperature of 125 °C.

The chemical content of the researched materials to identify chemical compounds in various areas of pipes were carried out by means of electron microprobe analysis using «Camebax» equipment. As a result of the study, no liquation in alloying elements was found. Impurities content in alloys composed less than 0.1 wt.%, and the content of the main chemical compounds in alloys is shown in **Table 1.**

Table 1 Actual and standard chemical compounds of researched alloys

Alloy grade	Material	Main chemical compounds content (wt.%)									
		Al	**Mg**	**Zn**	**Mn**	**Cu**	**Zr**	**Cr**	**Ti**	**Fe**	**Si**
2024	De facto	base	1.62	0.30	0.53	4.54	-	-	0.08	0.45	0.48
	ASTM B209M - 14	base	1.2-1.8	0.30	0.3-0.9	3.8-4.9	-	-	0.1	0.5	0.5
1953	De facto	base	2.6	5.7	0.17	0.45	0.02	0.19	0.05	0.1	0.05
	TU1-2-592-2003 standart	base	2.0-3.0	5.6-6.2	0.1-0.3	0.40-0.80	≤ 0.10	0.15-0.25	0.02-0.1	≤ 0.25	≤ 0.2

Two temperature and time operation modes, influencing a drill pipes material (200-250 °C, 2-10 min) and their further application in field development (150 °C, 1000 hours) were studied on the basis of the literature analysis.

Samples heating was carried out in a «SNOL-1.6.2.5. 1/11-E2» chamber furnace. The control of temperature was realized in a thermocouple soldered into the reference sample centre. The measurement accuracy accounted for ± 2.5 °C. The samples were preliminary placed into the furnace and heated to the specified temperature, then sustained for the definite time and cooled in the air. After heat treatment the mechanical properties were tested, and the alloys structure was analyzed.

The metallographic analysis of longitudinal and transversal samples was made by means of «Reichert-Jung MeF3A» optical microscope with magnification of 500 times using the automative quantitative images analysis software according to ASTM E 1245-03. Making and preparation of metallographic samples was realized using «Buehler» equipment according to ASTM E 3-95.

The phase analysis was made using a „DRON-3.0“ X-ray diffractometer with cooper emission for the general purpose.

Mechanical properties were defined with the help of the static test with uniaxial tension at the room temperature according to ISO 6892-84. The test was carried out with a «Schenck» tension testing machine with the maximal load of 200 kN and at the loading-rate of 1 mm/min.

Microhardness was measured using «Reichert-Jung Micro-Duromat 4000E» equipment with the help of the Vickers method according to ASTM E 92 procedure.

3. EXPERIMENTAL PART

The prior results, considering the studies of the precast drill pipes structure and properties made of 2024 and 1953 aluminum alloys after operation in oil field conditions development, showed that the mechanical properties and corrosion resistance of the metal is reduced after technological operations of assembly and drill pipe operation. The researched pipes were with the external diameter of 147 mm and the wall thickness of 13 mm for 2024 aluminum alloy, the life cycle accounted for 1003 hours in the conditions of oil well development.

Thereby, the aluminum pipe area threaded into a steel lock as well as the boundary contact area of the pipe and steel joint is exposed to the environment impact, temperature and external loads to the maximum in the process of assemblied drill pipe operation when developing oil and gas fields. In this regard, it is necessary to conduct systematic comparative studies to determine manufacturing conditions (shrink-type jointing) and drill pipes operation effect on the structure and properties of 2024 and 1953 aluminum alloys, especially in the contact area of the aluminum tube and steel lock.

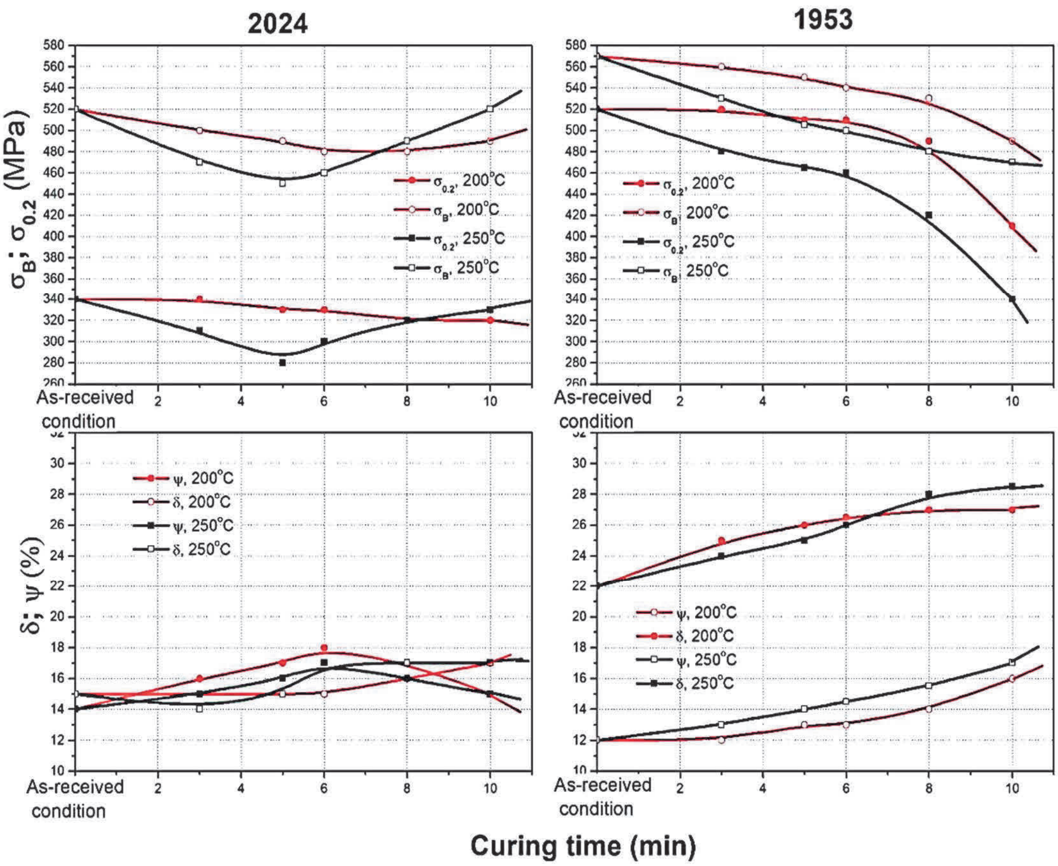


Figure 1 Technological heating duration and temperature effect on the mechanical properties of 2024 and 1953 alloys

The study of heating influence on the structure and properties of 2024 and 1953 aluminum alloys when manufacturing assemblied drill pipes presented in [6] allowed to establish that the heating process has a significant influence on the mechanical properties of drill pipes made of 2024 and 1953 aluminum alloys in the temperature range of 200 - 250 °C in the shrink-type jointing conditions during up to 10 minutes (**Figure 1**). The change of properties was due to diffusion processes, the nature of which differs in the investigated alloys.

Thereby, as a result of the „return during aging“ action and further dispersion hardening, the mechanical properties of 2024 alloy after heating up to ~ 6 minutes change insignificantly, but after 6-10 minutes the properties do not change compared to the as-the received condition (**Figure 1**). It is important that the increasing of heating temperature from 200 to 250 °C has an insignificant effect on the quantity value change of alloy strength and ductility. Due to this, 2024 alloy is resistant to technological heating in the conditions of drilling equipment installation and does not require tight regulation of temperature and time parameters of shrink-fit locking connection. Moreover, longer heating of up to 8-10 minutes is recommended.

The experimental data analysis shows that the aging process in 1953 alloy has the same tendency towards the decrease at the heating temperatures of 200 - 250 °C in the whole investigated range of shutter speeds. The release of secondary intermetallic compounds and coagulation of existing and additional particles occur after aging in the alloy structure. When the heating process lasts for at least 5 - 6 minutes, these processes are slow and practically do not influence the material properties. The increase of heating time by more than ~ 6 min significantly influence the aging process, especially at 250 °C, and coagulation of intermetallic compounds prevails over their allocation in the structure. As a result, heating with the duration of 6 - 10 minutes leads to significant softening of 1953 alloy.

The study of the structural stability and the changes of mechanical properties of 2024 and 1953 aluminum alloys after the process with subsequent heat maintenance simulating the conditions of drill pipes manufacture and operation during oil and gas development are presented in [7].

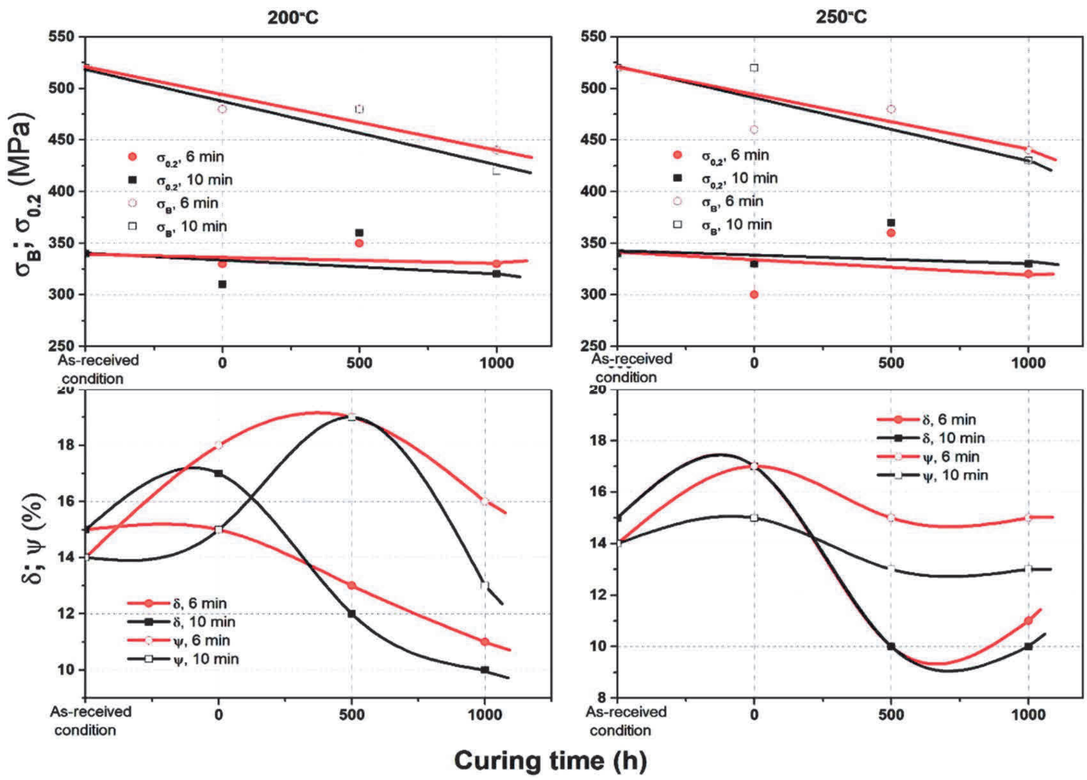


Figure 2 The effect of operating exposure duration at 150 °C on the mechanical properties of 2024 alloy after preliminary heating ("0" point) to 200 - 250 °C with the exposure of 6-10 min

The mechanical properties of 2024 alloy after heating, subsequent maintenance heating at the temperature of 150 °C and the exposure during 500 and 1000 hours are shown In **Figure 2.** It is obvious that the preliminary heating temperature increase from 200 to 250 °C and the exposure time increase from 6 to 10 minutes do not significantly affect the nature and intensity of changes in the mechanical properties of 2024 alloy with subsequent long-term operational exposure at 150 °C.

The experimental results show that the increase in the number of disperse particles in the structure of 2024 alloy occurs due to artificial aging at the initial stages at 150 °C and results in matrix solid solution hardening. As a result, the exposure time accounts for up to 500 hours and has little effect on the magnitude of σ_B and almost no changes in $\sigma_{0.2}$ alloy (**Figure 2**). The increase in exposure duration up to 1000 hours, accompanied by the beginning of secondary intermetallic compounds coagulation, leads to gradual alloy softening. However, this process in 2024 alloy is slow and does not lead to significant changes in mechanical properties.

1953 alloy aging during 500 hours at 150 °C leads to significant reduction in strength characteristics: σ_B - 70-110 MPa and $\sigma_{0.2}$ - 20 - 170 MPa regarding the material state after heating (depending on its mode) and by 140-160 MPa and 180 - 200 MPa concerning as-received condition (**Figure 3**). If one increases the exposure up to 1000 hours, alloy softening continues, but its intensity is significantly reduced. Plastic characteristics of 1953 alloy during aging at 150 °C gradually increase. After 1000 hours of exposure elongation δ increases by 1 - 3 %, and reduction of area ψ increases by 20 - 23 % compared to the material state after technological heating when elongation δ increases by 4 - 7 %, and reduction of area ψ increases by 24-29 % compared to as-received condition, respectively. It was noted, the increase in reduction of area values exceeds enormously the increase in relative elongation values. This indicates the strain coefficient decrease of alloy hardening.

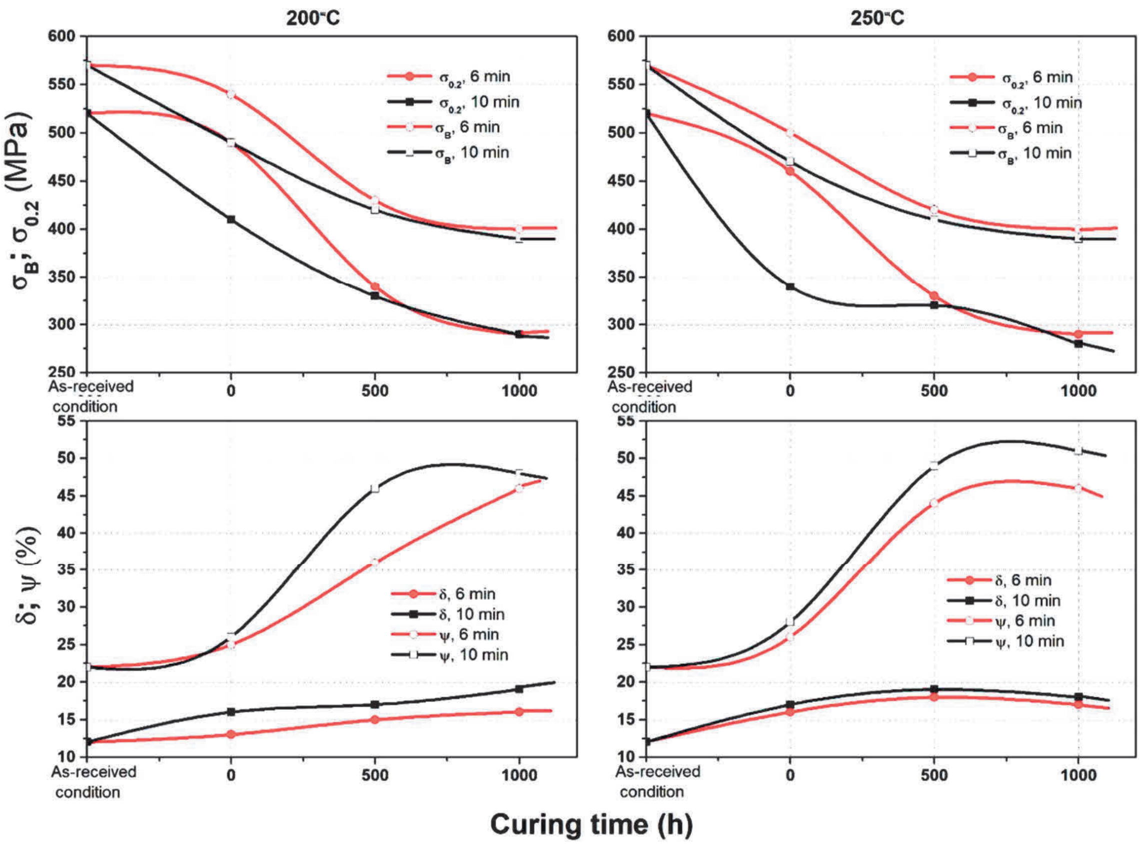
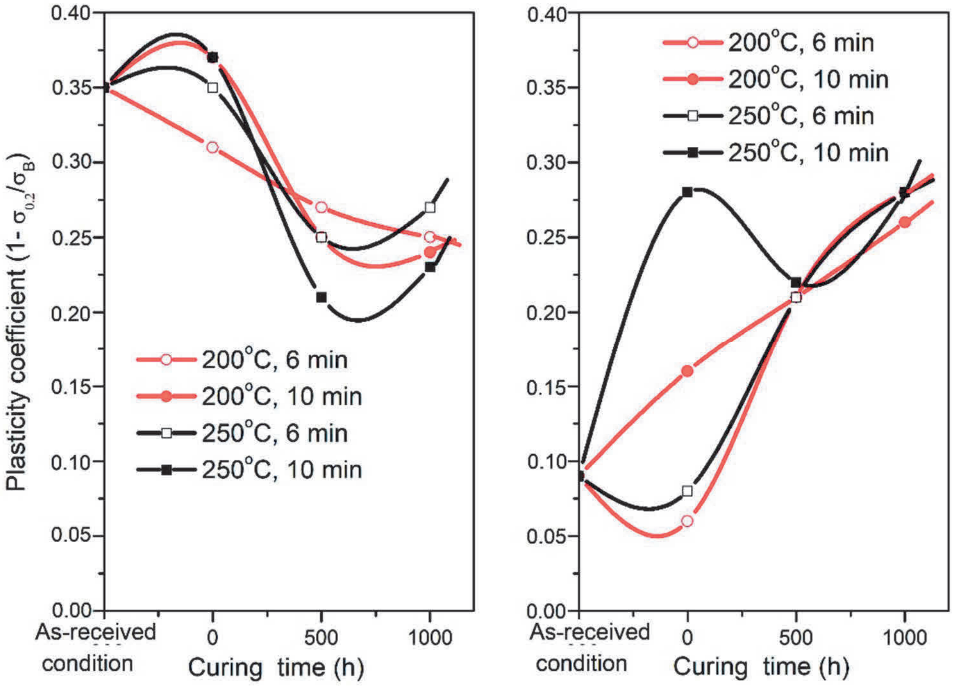


Figure 3 The effect of operating exposure duration at 150 °C on the mechanical properties of 1953 alloy after preliminary heating ("0" point) to 200 - 250 °C with the exposure of 6 - 10 min

Experimental data analysis testifies artificial aging intensiveness of 1953 alloy from the beginning of exposure and in the study time period at the operating temperature of 150 °C.

Being more durable compared to 2024 alloy in as-received condition, 1953 alloy has lower strength characteristics after short-term technological heating during manufacturing drill pipes and, especially, after long-term heating during operation. So, at the initial state ultimate strength σ_B and yield strength $\sigma_{0,2}$ of 1953 alloy are higher by 50 and 180 MPa than those of 2024 alloy. However, after technological heating and subsequent aging at the operating temperature of 150 °C during 500 hours ultimate strength and yield strength of 1953 alloy are lower than those of 2024 alloy by 30 - 40 and 30 - 60 MPa, respectively. 1953 alloy has lower operational characteristics compared to 2024 alloy, i.e. plasticity coefficient of 1 - $\sigma_{0.2}/\sigma_B$ (**Figure 4**).



(a) (b)

Figure 4 The effect of operating exposure duration at 150 °C on the plasticity coefficient (1 - $\sigma_{0.2}/\sigma_B$) of 2024 alloy (a) and 1953 (b) after preliminary heating ("0" point) to 200 - 250 °C with the exposure of 6 - 10 min

The experimental results show that 2024 alloy is more stable compared to 1953 alloy when these materials are used for manufacturing drill pipes in the oil and gas industry. 1953 alloy requires strict regulation of temperature and time parameters of manufacturing equipment and has lower operating resistance than 2024 alloy. So, 2024 alloy does not require tight regulation of temperature and time parameters of manufacturing equipment and has high operational stability. This allows us to consider it, first, more technologically advanced and, second, to recommend for manufacturing drill pipes that are designed for more complex operating conditions.

The influence of corrosive environment for oil and gas fields on the operational resistance of 2024 and 1953 aluminum alloys was studied. One of the stages of this study was to assess the influence of corrosive environment for oil and gas fields on corrosion, in general, and mechanical properties of 2024 and 1953 alloys, in particular.

Mechanical properties of 2024 and 1953 alloys after short preliminary heating and subsequent long-term heating in different modes in corrosive environment are shown in **Figure 5**. The comparison of these graphs shows the strength and plastic characteristics of the alloy under different conditions (initial value).

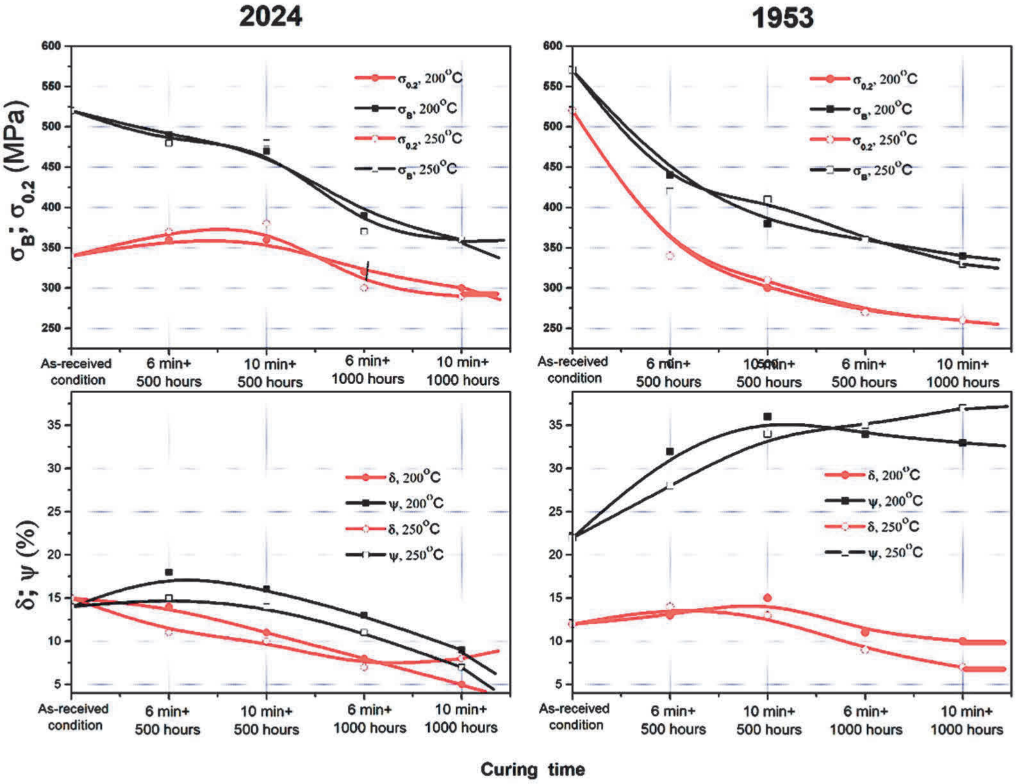


Figure 5 The influence of exposure duration of 500 or 1000 hours at 150 °C in NaCl + NaOH (pH = 11) on mechanical properties of 2024 and 1953 alloys after preheating (200 or 250 °C, 6 or 10 minutes)

Short-term technological heating with subsequent long-term operational heating in corrosive environment reduces the mechanical properties of the investigated alloys, and especially 1953 alloy, to a much greater extent. After testing the strength characteristics of 2024 alloy become higher than those of 1953 alloy that in the initial state had the advantage in mechanical properties.

Considering the provocative effect of the contact aluminum pipe with a steel lock in the process of operation of the drill string, it is necessary to assess alloy susceptibility of contact corrosion. Since the results showed that 1953 alloy is susceptible to general corrosion in the environment of oil and gas fields to a much greater extent than 2024 alloy, so the samples, made of 1953 alloy in as-received condition (drill pipe) in contact with 40CrNi2Mo steel samples (steel lock) were tested.

There are various techniques to eliminate contact corrosion; the most common one is protective coating on contacting parts surface. The experimental study showed that anodic oxidation of 1953 alloy leads to decrease in its corrosion rate in contact with 40CrNi2Mo in 5% NaCl steel solution.

4. RESULTS AND DISCUSSION

The result of the complex experimental researches of production conditions and drill pipe operation influence on the structure and properties of deformable 2024 and 1953 aluminum alloys were developed, and practical recommendations to increase their exploitation in developing oil and gas fields were offered.

The changes of structure and mechanical properties of 2024 and 1953 alloys for long exposure after short-term heating, simulating a shrink-fit, locking connection and subsequent operation of modular drill pipes in the conditions of oil and gas development were experimentally studied. It was shown that after natural aging 2024 alloy did not significantly change in its strength and ductility. Rapid processes of decay in 1953 alloy lead to sharp weakening.

The influence of corrosive environment of oil and gas fields on 2024 and 1953 aluminum alloys were experimentally investigated. It was shown that 2024 and 1953 aluminum alloys are stable under the operating conditions of hydrocarbon production.

5. CONCLUSION

The studies allow conclude that despite the established negative influence of corrosive environment of oil wells 1953 deformable aluminum alloy and, especially 2024 alloy, become quite stable after heating during manufacturing a drill pipe with a steel lock when operating hydrocarbon fields development.

It was established that 2024 and 1953 alloys are subjected to contact corrosion when operating assembly drill pipes in the conditions of oil and gas development, but the proposed oxidation of the contact zone leads to decrease in the corrosion rate, therefore, increasing the service life of drill pipes.

On the basis of the experimental studies and identified patterns the possibility to apply 2024 and 1953 aluminum alloys to manufacture precast drill pipes (with steel lock) when developing oil and gas fields was defined. The invalidity of pre-existing opinions about the advantage of 1953 alloy compared to 2024 alloy in the operating conditions of drill pipe is shown. Significant technological and operational advantages of 2024 alloy compared to 1953 alloy, especially when the drilling pipes of these materials are used for drilling in particularly difficult conditions, are experimentally proved.

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