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Development of a New Aluminium Alloy for Drill Pipes

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Abstract. The new aluminium alloy for drill pipes is one of the 6xxx-series alloys. The alloy has high strength properties at room and elevated temperatures, as well as high corrosion resistance and workability. Semi-finished extruded products from the new alloy have the following properties: UTS = 420 MPa, YTS = 380 MPa, elongation = 10% and YTS^{150} = 345 MPa, corrosion rate in solution (pH 11) = 0.09 g/m^2 h. Based on the obtained properties, the new alloy can be used as a replacement for D16 alloy.

1 Introduction

Steel pipes have always met all the requirements when used in wells drilled in shallow deposits. The use of aluminium pipes has not been very common. However, nowadays such deposits are almost exhausted and new ones are being developed intensively. The increased depth of such deposits (over 3500 meters) has affected the complexity of drilling conditions – the drilling depth has therefore significantly increased, and the practices of directional and subsea drilling have been launched [1, 2].

Modern drilling technologies are designed to increase the capacity of equipment and for the use of steel alternatives. Since the possibility of increasing the drive power is quite limited and economically impractical, the application of alternative steel materials – namely, aluminium alloys – becomes the most cost-effective and relevant target [3].

Aluminium alloys are still of relatively limited use in drilling, with the main ones being D16 and 1953 alloys. D16 alloy has high strength characteristics at room and elevated (up to 160° C) temperatures, medium ductility, but very low corrosion resistance in drilling fluids. 1953 alloy also has high strength properties at room temperature and good corrosion resistance, but it has low ductility (7%) and low strength at 150° C. The temperature is of crucial importance here, since in deep wells, depending on the geological section, the temperature at 3500-7000m can reach 150° C, and in some cases – 250-550° C [4, 5].

In contrast to these alloys, 6xxx-series aluminium alloys have high corrosion resistance and ductility. In addition, there are high alloys of this series that have the same strength characteristics as D16, namely 1370, 6069.

This article presents the findings of a study devoted to a new 6xxx-series aluminium alloy for drill pipes, which has mechanical properties at the level of D16, high corrosion resistance and operating temperatures of up to 150° C.

2 Methods and materials

The new 6xxx-series (Al-Mg-Si-Cu system) is alloyed with small additives of Mn, Cr, Ti and Ni. The semi-continuous casting of hollow ingots was performed in a DC mould. The hollow ingots were then homogenized at a temperature of 5-10 ° C below the nonequilibrium solidus temperature for 4, 6, 8 hours. After homogenization, the ingots were extruded into pipes with an external diameter of 100 mm and an internal diameter of 80 mm. The pipes were heat-treated under the following mode: quenching at T_{sol} – (5-10) ° C in water and aging at 170 - 175 ° C for 16 hours.

The optimal mode of homogenization was selected on the basis of the sphericity index FC:

$$FC = 4\pi \frac{F}{P_C^2}, \qquad (1)$$

where F is a particle surface;
P_C is the Crofton Perimeter.

Sections were made mechanically using sanding paper with SiC and polishing slurry with SiO2. Sections were etched with Keller's etch.

The microstructure was analysed using a Carl Zeiss Axio Observer optical microscope, in bright field.

Differential thermal analysis was performed with a NETZSCH DSC 404 F3 high-temperature calorimeter in a sealed Al2O3 crucible, with a continuous flow of argon.

The mechanical properties of tensile samples of pipes were determined at room and elevated (150 °C) temperatures using the MTS Criterion C45.105 universal testing machine with a climate chamber. The tested samples had cylindrical shape.

The general corrosion properties were tested by exposing to a solution of 5% NaCl + NaOH (pH = 11) for 30 days.

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3 Results and discussion

3.1 Homogenization

Due to nonequilibrium crystallization, the cast ingots have low ductility and corrosion resistance, as well as anisotropy of properties, which will negatively affect the process of extrusion. Homogenization annealing will help eliminate these deficiencies. The homogenization temperature was determined based on the DSC curve of a cast sample. The results are shown in Figure 1.

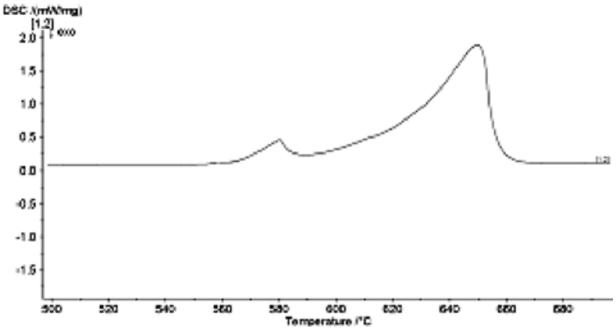

Fig. 1. DSC curve, as-cast alloy.

The DSC curve shows that the temperature of the nonequilibrium solidus of the new alloy is in the range of 550-600° C. To avoid burning, the homogenization temperature was set at (5-10)°C below nonequilibrium solidus. The exposure time was selected experimentally, based on the transformation ratio of needle-shaped glandular phases (FeAl3 and β-Al5FeSi). It takes quite a long time for these phases to change due to the slow diffusion of iron in aluminium. For this reason, cast samples were exposed to homogenization temperature for 4, 6, 8 hours before the microstructure analysis.

Figure 2 shows the alloy structure after casting and homogenization for 4, 6, 8 hours.

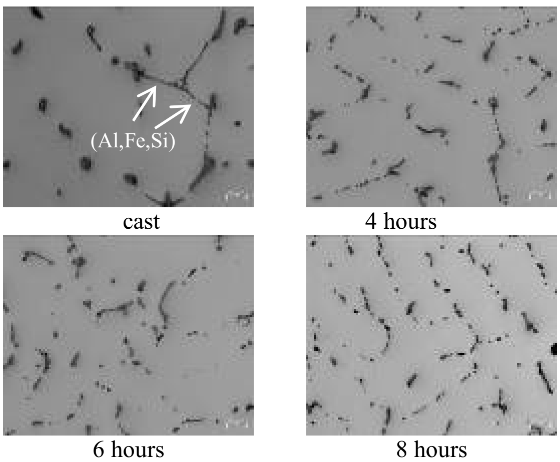

Fig. 2. Alloy structure after casting and homogenization at T - (5-10) °C below nonequilibrium solidus for 4, 6, 8 hours, X1000.

Figure 2 shows that the change in structure is already visible even in case of 4h exposure, and in 8 hours 90% of the glandular phases are already fragmented. In this case, the sphericity index FC varies from 0.35 (cast) to 0.88 (exposure for 8 hours). Thus, the optimum exposure time at homogenization temperature is 8 hours. A further increase in the exposure time will not lead to any significant changes in the glandular phases. However, it will significantly increase the grain size and gas saturation of ingots, which is unacceptable.

After homogenization, hollow ingots were extruded into pipes with an external diameter of 100 mm and an internal diameter of 80 mm.

3.2 Heat treatment

Upon extrusion, drill pipes must undergo heat treatment (hardening and aging) to obtain the necessary mechanical and corrosion properties. DSC analysis of extruded pipe samples was performed in order to determine the quenching temperature. The DSC curve is shown in Figure 3.

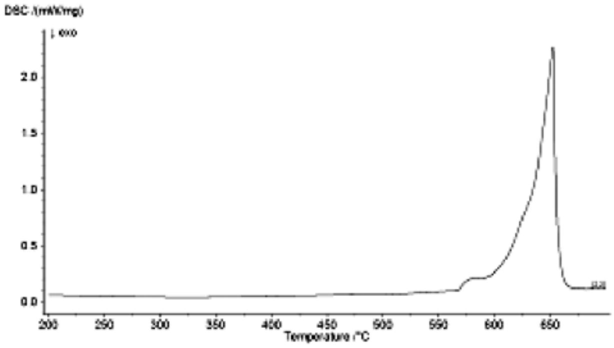

Fig. 3. DSC curve of extruded pipes.

The solidus of the alloy extruded into the semi-finished product is in the same temperature range as the homogenization temperature, 550-600 °C. The quenching temperature for the alloy must not exceed this limit in order to avoid burnout. The quenching temperature was set as per T_{sol} – (5-10) °C. The time of exposing extruded pipe samples to the set temperature was calculated taking into account the maximum saturation of the solid solution with alloying elements (mainly due to the dissolution of the Mg_2Si phase). The samples were quenched in water and then artificially aged under 170-175 °C for 16 hours. This mode was also applied for 6069 alloy [6], which is similar to the tested one.

After heat treatment, the structure remains unrecrystallized with a visible effect of extrusion (see Fig. 4). The effect of extrusion increases mechanical properties of the pipes by preserving the cast structure.

3.3 Mechanical properties

In order to determine the mechanical properties, tensile test was performed for the heat-treated samples at room and elevated (at 150°C) temperatures. These characteristics of the material, along with corrosion resistance, are crucially important for drill pipes, since they are used in mechanical design of drilling strings [7]. The test results are presented in Figure 5. Mechanical properties of pipes extruded of D16 and 1953 alloys (they are currently used) are also presented here for the sake of comparison.

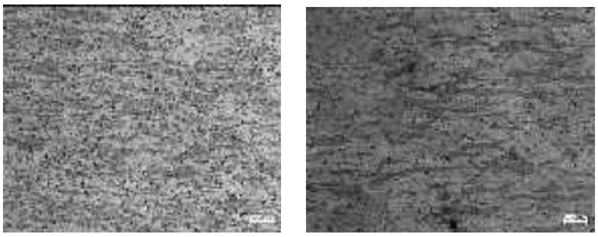

Fig. 4. Structure of the extruded pipes before (a) and after (b) heat treatment at 565 ºC, 1 h, quenching in water + aging at 170-175 ºC, 16 h, x100.

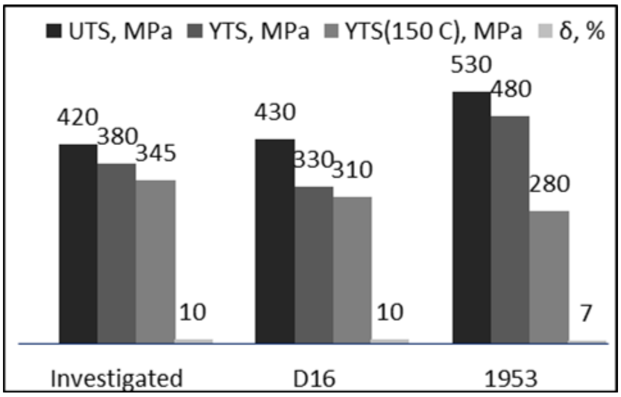

Fig. 5. Mechanical properties of aluminium alloys used for extruding drill pipes.

Despite the same tensile strength and ductility of the tested alloy and D16 alloy, the former has significant advantages in terms of other properties. The yield strength of the new alloy is 13% higher at room temperature and 10% higher at a temperature of 150 ° C. Increased strength at elevated temperatures makes this alloy more applicable for drilling ultra-deep wells.

The strength properties of 1953 alloy at room temperature are significantly higher than those of D16 alloy and the tested alloy. However, at a temperature of 150 °C this alloy has a significantly lower strength (280 MPa) compared with the new alloy and D16. The change in strength at high temperature is caused by different rates of diffusion processes in the alloys under consideration [8, 9, 10]. In 1953 alloy, due to the rapid processes of separation of intermetallic compounds and their subsequent coagulation at a temperature of 150 °C, the properties decrease more rapidly than those of the other alloys under consideration. Intermetallic compounds in D16 alloy and in the new one are more stable under these conditions; therefore, the strength properties remain high.

As a result, due to its mechanical properties, the new alloy has advantages over D16 and 1953.

3.4 Corrosion rate

The low corrosion rate in drilling fluids is one of the main requirements for the material used for manufacturing drill pipes, since drilling pipes are exposed to a corrosive medium (drilling fluid) with different pH levels. The pH of the drilling fluid has a wide range from 4 to 10.

According to published sources [11], aluminium alloys have high corrosion resistance in various aggressive media, a drilling fluid with pH of 4 to 10, due to the presence of the aluminium oxide film on their surface. In the range of less than 4 and more than 10, aluminium oxide becomes unstable, and the corrosion resistance of aluminium alloys noticeably deteriorates.

Another advantage of aluminium alloys is the absence of corrosion damage when being exposed to a medium fully saturated with hydrogen sulphide and carbon dioxide, where steel pipes are prone to corrosion cracking. Such findings are presented in the article [12].

Table 1 shows the corrosion rate of aluminium alloys in solutions with different pH levels. The table shows that a solution with pH = 11 has the highest corrosion, therefore, the new alloy was compared to D16 and 1953 alloys by exposing to this specific solution. The results are presented in Fig. 6.

Table 1. Corrosion rate of aluminium alloys for drill pipes at different pH levels [11].

Alloy	Corrosion rate, $g/m^2 \cdot h$			
	pH=11	pH=7	pH=2.5	H_2S
D16	0.49	0.01	0.05	Not
1953	0.21	0.02	0.04	

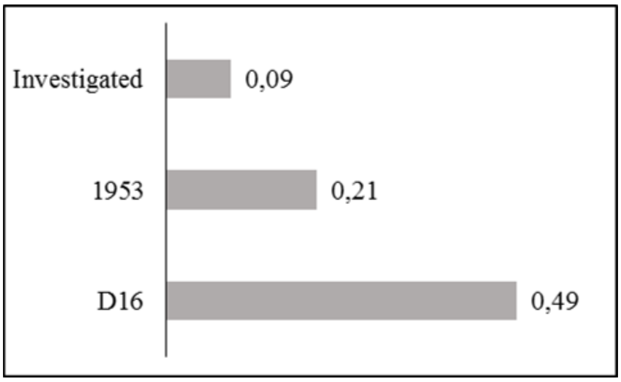

Fig. 6. Corrosion rate of aluminium alloys, g/m^2 h.

As shown in Figure 6, the corrosion rate of the investigated alloy is significantly lower than the one of 1953 and D16. Thus, pipes from the new alloy will be less prone to corrosion than pipes from the currently used alloys.

Due to higher corrosion resistance of and equal mechanical properties, we can consider replacing the D16 with the new 6xxx-series alloy.

4 Conclusion

1. A new 6xxx-series aluminium alloy for drill pipes has high workability, strength (at room and elevated temperatures), and corrosion resistance. Pipes from the new heat-treated alloy have the following properties: UTS = 420 MPa, YTS = 380 MPa, elongation = 10% and YTS150 = 345 MPa.

2. The new alloy has significantly greater corrosion resistance in the solution with pH = 11 (0.09 g / m2 h), compared with currently used D16 (0.49 g / m2 h) and 1953 (0.21 g / m2 h) alloys.
3. The new alloy has higher strength at 150 °C than D16 and 1953 alloys, by 10% and 19%, respectively.
4. Due to its high properties, the developed alloy can be used in replace of D16 alloy.

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