Operational properties of drill pipes made of coated aluminum alloy 2024

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Abstract. The main aim of this article is to provide for the comprehensive study that has been carried out. We tested the performance characteristics of coated aluminum alloy 2024 under conditions simulating the operation of drill pipes in the oil industry. In the course of our study we experimentally determined electrochemical potential and corrosion rate of the coated aluminum alloy 2024. Moreover, a comparative analysis of adhesion and wear resistance of coatings during the use of the alloy has been carried out. The authors have also studied structures of various coatings and the nature of damage to aluminum alloy drill pipes under operation.

1. Introduction
The increasingly complex conditions for oil and gas wells drilling require the use of new materials to manufacture drill pipes and the reasonable choice of such materials in order to comply with specific operational conditions [1-6]. Aluminum alloys (in comparison with steel) can be considered as the most promising materials for the production of drill pipes that are used in oilfield development [7-11]. Despite demonstrating a higher specific strength and corrosion resistance [12-13], aluminum drill pipes are inferior to steel ones in terms of durability. Thermal treatment, cold deformation, surface toughening, etc [14-17] are used to increase the wear resistance of aluminum pipes. However, it is most economical to apply a protective coating on the metal of the pipe. Such coating should have the necessary adhesion with the main metal and the continuity and the technology of its application should not change the service properties of the substrate. There is little information in the literature on how the protective coatings affect aluminum drill pipes, so our study is obviously seen as a relevant one. The purpose of the study is to investigate the performance of aluminum drill pipes covered with various protective coatings.

2. Research material and methodology
We tested drill pipes (147 mm and 126 mm in diameter) made of aluminum alloy 2024 under tempering (hardening and natural ageing). Chemical composition of the pipe material (table 1) is consistent with the standard aluminum alloy 2024 (GOST 4784-97). We used various mixtures provided by three manufacturers to apply coatings with high-speed flame spraying. P and K coatings
were applied to the tubular blank of the aluminum alloy 2024 in the after quenching and natural aging state, and G coating was applied to the blank subsequent to annealing.

We carried out metallographic analysis of the alloy longitudinal and transverse grinding with «Reichert-Jung Mef3a» optical microscope (x 100-500 zoom). SUPRA 55/55VP autoemission raster electron microscope was used to determine chemical composition of the coatings. We used equipment of the «Buehler» company to manufacture and prepare all the metallographic grinders according to the ASTM E 3-95.

| Table 1. Real chemical composition of the aluminum alloy 2024 samples covered with various coatings. |
|----------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| Alloy type     | Coating material | Basic chemical element content, mass. % | Al | Mg | Zn | Mn | Cu | Cr | Ti | Fe | Si |
| Aluminum alloy 2024 (Base P) | P 1 | Base | 1.59 | 0.24 | 0.49 | 4.39 | 0.02 | 0.04 | 0.23 | 0.20 |
|                 | P 3 | Base | 1.50 | 0.05 | 0.67 | 4.89 | 0.01 | 0.04 | 0.44 | 0.24 |
| Aluminum alloy 2024 (Base K) | K 1 | Base | 1.50 | 0.15 | 0.78 | 4.79 | 0.03 | 0.06 | 0.08 | 0.06 |
|                 | K 2 | Base | 1.57 | 0.16 | 0.70 | 4.75 | 0.03 | 0.06 | 0.08 | 0.03 |
|                 | K 3 | Base | 1.57 | 0.12 | 0.75 | 4.68 | 0.01 | 0.05 | 0.06 | 0.07 |
| Aluminum alloy 2024 (Base G) | G 1 | Base | 1.26 | 0.14 | 0.64 | 4.71 | 0.04 | 0.09 | 0.14 | 0.08 |
|                 | G 2 | Base | 1.25 | 0.13 | 0.68 | 4.20 | 0.03 | 0.09 | 0.15 | 0.05 |
|                 | G 4 | Base | 1.32 | 0.14 | 0.73 | 4.81 | 0.03 | 0.03 | 0.05 | 1.99 |

The electrode potential of the metal was measured in a 5% sodium chloride solution using three samples per each coating type. The potential was measured with a high-resolution voltmeter using a standard silver chloride comparison electrode that features its own potential relative to a standard hydrogen electrode of -0.200 V. The experiment lasted 120 hours. The electrode potentials of the samples were measured during 60-minute time period every day.

The rate of corrosion of the «metal-coating» pair by mass loss was determined in accordance with the requirements of ASTM G71-81 standard and calculated according to GOST 9.908-85 formula (1):

\[ V_{cor} = \frac{(m_k - m_0)}{St}. \] (1)

Where \( V_{cor} \) is the corrosion rate, g/m² per hour; \( m_k \) is the mass of the sample after the test, gram; \( m_0 \) is the mass of the sample before the test, gram; \( S \) is the surface area of the sample, m²; \( t \) is the testing period, hour.

The microhardness was determined on the basis of the Vickers method with the use of «Reichert-Jung Micro-Duromat 4000E» device following ASTM E 92 procedure. Mechanical properties of coated alloys were determined while performing the three-point bending tests [18]. Taking the geometry of each sample into account, we used a finite-element method and Cosmos Works package to calculate stress during testing.

We carried out durability tests of the coatings using a test bench. The test bench is equipped with three engines that allow rotating the shaft with the testing body (TB), rotating the counter face (CF) by means of a coggined pinion and chain gear and moving the TB against the CF simultaneously. The test conditions for coating durability are as follows: TB pressurization force to CF: 100 kg-wt; TB rotation speed: 100 rpm; TB displacement speed along the shaft: 3 m/h; CF rotation speed: 0.1 rpm; washing fluid: water. Control panel is used to ensure control over the measured parameters (frictional moment, clamping force and shaft speed) and to control engines that provide three types of movement (rotation...
and longitudinal movement of the sample, and rotation of the CF). Dacell TMS Ver 1.1 software is used to process sensor incoming data. The data are stored in files in tables and graphs.

3. Research findings and discussion
Figure 1 and table 2 show the micro-structure and the microhardness values of the alloy covered with different coatings. The alloy structure consists of $\alpha$-solid solution grains and inclusions of intermetallics. Anisotropy of the deformed alloy is more apparent in the tempered and aged state. Intermetallic phases are more evenly distributed over the thickness and length of the heated pipe blanks. Hence, the microhardness of the heated alloy covered with G coatings is significantly lower than the tempered and aged alloy covered with P and K coatings.

![Figure 1](image)

**Figure 1.** Micro-structure of aluminum alloy 2024 covered with P coating (a) after quenching and natural ageing and covered with G coating after annealing (b): longitudinal section (a) and cross-section (b).

| Coating | Microhardness HV, Pa |
|---------|----------------------|
| P 1     | 1400-1550            |
| P 3     | 1350-1450            |
| K 1     | 1350-1500            |
| K 2     | 1400-1550            |
| K 3     | 1400-1500            |
| G 1     | 750-850              |
| G 2     | 730-780              |
| G 4     | 710-770              |
Figure 2. Microstructure of P 1 (a, b) P 3 (c, d) coatings: optical microscope (a, c); electronic microscope (b, d).

The microstructure of the P 1 coating (Figure 2, a-b) with a thickness of 120 μm is composed entirely of WC (tungsten carbide) representing its high microhardness of 11.300 HV. The coating is homogeneous over the entire surface of the sample and a small number of pores are evenly distributed over the section and the length of the coating; the amount of porosity is 1.94%. The microstructure of P 3 coating (Figure 2, c-d) contains: ~ 50 vol. % of WC (tungsten carbide) with hardness of 12.000 HV and ~ 50 vol. % of Ni-Cr-Si connection with hardness of 8700 HV. The porosity of this coating (3.25 %) is greater in comparison with P 1 coating, and its thickness is 160 μm.

Figure 3 presents K 1, 2 and 3 coatings. K 1 coating structure is homogeneous; porosity is 0.038%; thickness is 80 μm. This coating consists entirely of WC (tungsten carbide); its hardness is 12300 HV. The structure of K 2 coating (thickness is 160 μm) consists of two components: ~ 53 vol. % of WC (tungsten carbide) with hardness of 12,000 HV and ~ 47 vol. % of Ni-Cr-Si mixture with hardness of 8700 HV. The porosity of the coating increases from 0.032% in the center to 0.21% on the surface. K 3 coating structure consists mainly of the Ni-Cr-Si mixture with hardness of 6300 HV, and a small amount (~ 3.98 vol. %) of Al2o3 oxide, which forms conglomerates. K 3 coating porosity is 4.45%, and its thickness is 170 μm.
Figure 3. Micro-structure of K 1 (a), K 2 (b), K 3 (c) coatings.

Figure 4 shows the micro-structure of G 1, 2 and 4 coatings. The structure of the G 1 coating consists of two layers: an outer layer (with a thickness of up to 30 μm) consists of WC (tungsten carbide) with a hardness of 11.600 HV, and an inner layer consists of a mixture of the Ni-Cr-Mo system with a hardness of 5.500 HV. The average surface porosity is 0.54% and is concentrated mainly in the inner layer. The total thickness of the coating is 120 μm; the thickness of the outer layer is 25-30 μm. The continuity of this layer is low. The microstructure of G 2 coating (140 μm thick) is homogeneous and consists of a Fe-Cr-Ni mixture (microhardness is 7900 HV; porosity is 0.083%). The microstructure of G 4 coating (326 μm thick) is also relatively homogeneous and consists of WC (tungsten carbide) (hardness is 12.900 HV; porosity is 0.76%).
Figure 4. Microstructure of G 1 (a, b) . G 2 (c) . G 4 (d) coatings: optical microscope (a, c, d); electronic microscope (b).

Having compared the results of metallographic analysis (table 3), we can conclude that K 1 coating is the best one according to the studied characteristics. Performance of P 1, K 2, G 2 and G 4 coatings is also sufficient. Due to the low continuity of the outer layer and the low hardness of the inner layer, G 1 coating is not recommended to use in practice.

| Table 3. Qualities of the surfaces examined |
|--------------------------------------------|
| Coating title | Coating composition | Structural homogenity | Porosity, % | Microhardness, HV, Pa |
|----------------|---------------------|----------------------|-------------|----------------------|
| P 1            | WC                  | +                    | 1.94        | 11300                |
| P 3            | WC                  | -                    | 3.25        | 12000                |
|                | Ni-Cr-Si            | -                    |             | 8700                 |
| K 1            | WC                  | +                    | 0.04        | 12300                |
| K 2            | WC                  | -                    | 0.03        | 12000                |
|                | Ni-Cr-Si            | -                    | 4.45        | 6300                 |
| K 3            | Ni-Cr-Si            | -                    |             |                      |
| G 1            | WC                  | +                    | 0.54        | 11600                |
|                | Ni-Cr-Ni-Mo         | -                    |             | 5500                 |
| G 2            | Fe-Cr-Ni            | +                    | 0.08        | 7900                 |
| G 4            | WC                  | +                    | 0.76        | 12900                |
Figure 5 shows the values of electrode potentials of aluminum alloy 2024 with and without different coatings. If the aluminum alloy 2024 is not covered with a coating, its electrochemical potential is 580-612 mV, which is more than 100 mV negative than its values for coated alloy 2024. Consequently, the aluminum alloy will be corrosion-soluble at the contact point with the coating. Therefore, in order to determine the contact corrosion rate of the samples mass loss, we only considered the surface area of the aluminum sample not covered with a wear-resistant coating.

![Figure 5. Values of electrode potentials of aluminum alloy 2024 (table 1) with and without different coatings.](image)

The results of the bi-metallic corrosion tests showed that the coatings contribute (at the point of contact with the main metal) to some increase in the corrosion rate of the aluminum alloy 2024 from 0.06 mm/year to 0.08-0.12 mm/year. We can come to a conclusion that a groove up to 1 mm deep may appear at the point of contact with the aluminum alloy coating in 8-12 years.

![Figure 6. Corrosion rate of aluminum alloy 2024 (table 1) with and without different coatings.](image)

Table 4 shows the results of three-point bend tests of coated aluminum alloy 2024. G1 and G2 coatings have the maximum deflection to the fracture formation and the highest breaking stress level of 1040 MPa. P 1, G 4, K 1 and K 3 coatings have average breaking stress level; P 3 and K 2 coatings feature the lowest breaking stress level.
Table 4. Results of three-point bend tests of coated aluminum alloy 2024

| Coating | Maximum breaking stress level of the coated area, MPa |
|---------|------------------------------------------------------|
| P1      | 1000                                                 |
| P3      | 800                                                  |
| G1      | 1040                                                 |
| G2      | 1040                                                 |
| G4      | 1000                                                 |
| K1      | 1020                                                 |
| K2      | 980                                                  |
| K3      | 1020                                                 |

Table 5 represents the results of depreciation tests of coated aluminum alloy 2024. It is obvious that P1, K1 and G4 coatings are the most wear-resistant ones.

Table 5. Results of aluminum alloy 2024 wear-resisting properties tests

| Coating | Marking | Weight loss, g | Test period, min |
|---------|---------|----------------|------------------|
| P1      | P1.1    | 2.4            | 240              |
|         | P1.2    | 0              | 480              |
|         | P1.3    | 0.3            | 480              |
| P3      | P3.1    | 6.2            | 120              |
|         | P3.2    | 8.7            | 480              |
|         | P3.3    | 6.9            | 480              |
| G1      | G1.1    | 0.2            | 30               |
|         | G1.2    | 0.7            | 30               |
| G2      | G2.1    | 12.5           | 30               |
|         | G2.2    | 19.5           | 30               |
| G4      | G4.1    | 0              | 480              |
|         | G4.2    | 0              | 480              |
|         | G4.3    | 0              | 480              |
| K1      | K1.1    | 0.1            | 480              |
|         | K1.2    | 0              | 480              |
|         | K1.3    | 0              | 480              |
| K2      | K2.1    | 31.5           | 30               |
|         | K2.2    | 10.6           | 30               |
|         | K2.3    | 9.8            | 30               |
| K3      | K3.1    | 2.2            | 480              |
|         | K3.2    | 2.2            | 480              |
|         | K3.3    | 2.2            | 480              |

We measured surface roughness with MarSurf 1 profilometer in order to compare specific features of worn out surfaces of coatings. Table 6 shows the results of roughness measurements.
### Table 6. Assessment of surface roughness of aluminum alloy 2024 coatings (after wear tests)

| Coating type | Profile chart | Ra . µm |
|--------------|---------------|---------|
| P1           | ![](image)    | 3.4     |
| K1           | ![](image)    | 1.3     |
| G4           | ![](image)    | 0.3     |

G4 coated alloy samples have the smallest roughness value (Ra). P1 and K1 coated alloy samples appeared to have significant local depreciation areas of up to 20 µm.
To summarize the results of the complex study of aluminum alloy 2024 coatings, it is possible to rank their performance on a scale of one to ten (Table 7).

**Table 7. Totals for the operational characteristics study of coated aluminum alloy 2024**

| Coating | Corrosion resistance | Stress-related properties | Wear-resisting properties | Total |
|---------|----------------------|---------------------------|---------------------------|-------|
| P1      | 9                    | 9                         | 8                         | 26    |
| P3      | 9                    | 8                         | 5                         | 22    |
| G1      | 9                    | 10                        | 1                         | 20    |
| G2      | 9                    | 10                        | 1                         | 20    |
| G4      | 9                    | 9                         | 10                        | 28    |
| K1      | 9                    | 9                         | 9                         | 27    |
| K2      | 9                    | 8                         | 1                         | 18    |
| K3      | 9                    | 9                         | 7                         | 25    |

4. Conclusion
Having carried out a study of the operational characteristics of coated aluminum alloy 2024 to be used as drill pipe material, the authors may conclude the following. All the coatings examined increase the properties of aluminum drill pipes, but the effectiveness of the influence depends on their composition and structure. The corrosion and mechanical properties of the alloy are comparable across all coatings, but their impact on wear resistance varies considerably. To use WC (tungsten carbide) coated aluminum alloy 2024 as a drill pipe material would be the most beneficial for petroleum production. In contrast, WC+Ni-Cr-Si coating is the least recommended one.

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