Advanced Aluminum Alloy Oil Pipelines for Polar Regions: Material Innovation and Production Strategies

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Abstract. Oil transportation in polar and subpolar regions poses significant challenges due to extremely low temperatures and corrosive environments. This paper addresses these challenges by exploring the design and development of aluminum alloy pipelines, focusing on Al7075 as a lightweight and corrosion-resistant alternative to traditional carbon and alloy steels. The study investigates a modified aluminum binary alloy formula aimed at enhancing low-temperature toughness and resistance to corrosion. Advanced manufacturing techniques such as rapid solidification and hot forming with an in-die quenching process are applied to refine the alloy's microstructure and improve its mechanical properties. A novel concrete-filled double-skin aluminum alloy tubular design is introduced, providing additional strength and flexibility to withstand high pressures and shear forces. Furthermore, a Co-Ti-Mo conversion coating is utilized to enhance the corrosion resistance of the pipelines, showing up to five times greater protection against pitting. This research offers a comprehensive solution for improving the durability and efficiency of aluminum alloy pipelines in harsh polar environments, paving the way for safer offshore oil transportation.

Keywords: Oil pipeline; aluminum alloy; alloy design; polar region.

1. Introduction

Polar regions are often praised as the world's resource bank. There are many resources, such as oil hidden under the ice and ocean. Engineers have also produced many ways to exploit these resources, including offshore drilling platforms, deep-sea oil fields, etc. Due to their working environment, these facilities also have very high requirements for the materials used. The development of oil tubes for polar regions presents a unique set of challenges that engineers and designers must navigate to ensure functionality and safety in extreme conditions. The harsh environments characterized by low temperatures, ice, and oceanic environments demand materials and designs that can withstand significant stress. Overall, the primary materials used in oil tube making include carbon steel and various alloy steel grades for their low price and high toughness. However, in some scenarios, the heavyweight and relatively low strength can limit the application of steel.

Aluminum alloys are widely used in applications such as oil pipelines and ship structures as a substitution for steel due to their lightweight, high specific strength, excellent corrosion resistance, and good machinability [1]. The material exhibits higher strength in extremely low-temperature environments, particularly due to the "double strengthening effect" of aluminum alloys (i.e., the increase in yield and tensile strength as temperature decreases). In the challenging environment of polar/subpolar regions, the need for reliable and durable oil transportation systems is of paramount importance. So, selecting aluminum also necessitates careful consideration of design aspects such as thermal expansion, mechanical strength, and resistance to environmental factors.

In this exploration, some specific challenges posed by polar environments will be considered. Examining the materials commonly employed in oil tube construction will highlight the potential benefits of using aluminum in these conditions. By taking the experience from previous studies on the mechanics of aluminum alloy, this paper proposes a design for an aluminum alloy oil pipeline tailored explicitly for these extreme conditions. The base material is Al7075 aluminum alloy. This alloy already possesses several desirable properties, such as high strength and good mechanical performance [2]. However, to further enhance its suitability for polar regions, the formula for the alloy will be modified to boost its mechanical properties, especially in low temperatures. It ultimately provides insight into the expected outcomes for aluminum oil tubes in the unforgiving polar climate.

2. Environment Harshness

2.1. Low temperature

At extremely low temperatures, the activity of atoms inside the material is weakened, and dislocation movement becomes difficult, which makes it difficult for the material to undergo plastic deformation when subjected to external forces, thereby showing reduced toughness. According to research, at low temperatures, brittle fractures occur in impact tests, while at room temperature, most fractures are ductile fractures. This may be due to the low-temperature, brittle nature of aluminum alloys. The ductile-to-brittle transition occurs in the range from room temperature to -100 ℃ for several aluminum alloys tested, depending on the magnesium content. It is worth noting that Al-6Mg alloy begins to transition at -70 ℃, which is much lower than other alloys with magnesium content, so Al-6Mg alloy has better impact toughness at lower temperatures [3]. Additionally, the alloy needs to have sufficient strength to withstand the internal pressure of the oil and any external loads. The strength of aluminum alloy oil pipes will be significantly affected, which also poses higher requirements for the connection parts of aluminum alloy oil pipelines.

2.2. Oceanic Corrosion

For alloys used in marine or coastal environments, corrosion resistance is an important issue because the humidity, salt, and even microorganisms brought by the marine environment have an accelerated corrosion effect on the alloy [1,4]. According to Alqahtani et al., the oxide layer formed on aluminum alloys usually has excellent corrosion resistance. However, the surface of the metal is not always uniform. Intermetallic compounds, Mg_2Si phases, and AlFeSi particles can cause local corrosion. Due to their higher electric potential, they attract chloride ions in seawater, and the chloride ions react with the oxides in the oxide film, resulting in the dissolution of the oxide film and the formation of pits [1]. Pits specifically refer to the internal cavities that appear in the material under corrosive conditions, which can usually penetrate the surface of the material or even penetrate the material, destroying the integrity of the material.

3. Alloy Design

Among all aluminum alloy pipes, Al7075 is usually used as an oil pipe because of its good ductility and strong corrosion resistance [2]. However, under the extreme conditions of polar ocean areas, Al7075 cannot perfectly adapt to this working environment. Its toughness at low temperatures is not outstanding, and its resistance to seawater corrosion also needs to be improved. For enhancement of the alloy, the feature can be examined by looking at the binary alloys with some of the main compositions in Al7075.

3.1. Binary Alloys

3.1.1 Al-Cu

Aluminum and copper alloys have a wide range of applications, especially because they combine the excellent properties of aluminum and copper. From the binary phase diagram of copper and aluminum, it can be clearly seen that in the solid solution phase, as shown in Fig. 1, copper and aluminum will combine to form Al_2Cu precipitates, thereby greatly improving the strength of the alloy. Al_2Cu is one of the most common and effective precipitation strengtheners. In the aluminum substrate, Al_2Cu will exist in a plate-like structure with a very high aspect ratio, which can effectively hinder the propagation of dislocations [5].

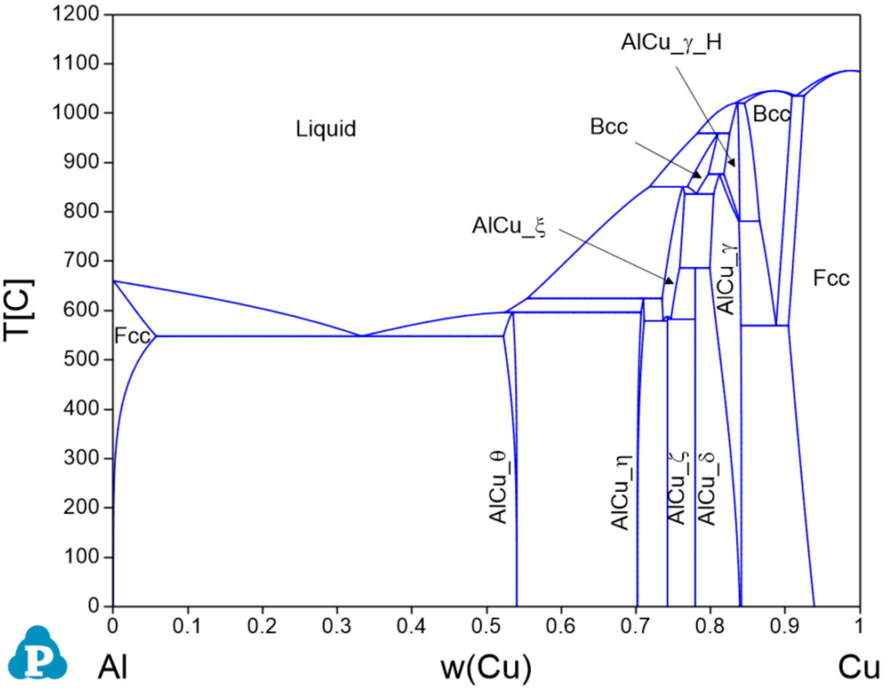

Fig. 1 Phase diagram of Al-Cu [6]

3.1.2 Al-Mg

Increasing the magnesium content in the aluminum alloy (0%-10%), according to Fig. 2, it can be observed that the grains of the alloy gradually become smaller, and the reduction in grain size means higher strength due to boundary effects [3]. According to Alqahtani, a smaller grain size means that the alloy will have higher ductility, making it more likely that the alloy will fracture ductile rather than brittlely when subjected to impact, giving the alloy higher toughness and strength [1]. This is also consistent with Kwangtae Son's experiment. The data showed that when the magnesium content in the alloy increased from 3.5% to 6%, the impact toughness was greatly improved, especially in the range of room temperature to -100 ℃ [3]. However, as the magnesium content further increased to 8.5%, the impact toughness decreased. According to Kwangtae, the weaker and randomly distributed texture of Al-6 Mg alloy compared to the higher Mg continent might contribute to this phenomenon.

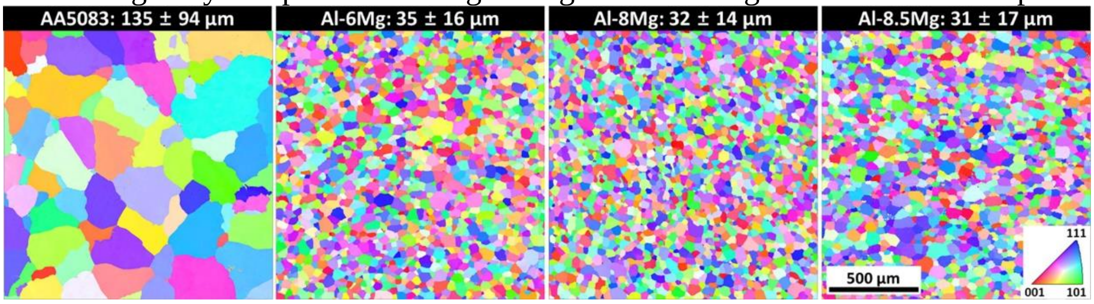

Fig. 2 Gain size of AA5083, Al-6Mg, Al-8Mg, Al-8.5Mg alloy [3]

3.1.3 Al-Zn

Studies have shown that adding zinc to aluminum-magnesium alloys can further increase the strength of the alloy because, in the aluminum substrate, zinc can react with part of magnesium to synthesize $MgZn_2$ [5], which can form a supersaturated solid solution (SSSS) microstructure in the alloy, giving the alloy higher strength [7]. However, at the same time, studies have shown that as the proportion of zinc in the alloy increases, the alloy will produce more pits. In an environment with anions, ZnO will cause film defects on the alloy surface, making it easier for anions to enter the alloy and cause pits [8].

Another factor to be considered is the silicon content. The silicon in the alloy will react with magnesium, aluminum and iron to form Mg_2Si and AlFeSi, which will cause local corrosion [1]. Local corrosion will further develop into pitting corrosion. Therefore, the silicon content in the new alloy should be reduced.

Combining all the features concluded in previous sections, the modification to the alloy composition of the Al7075 alloy to mostly fit the polar/sub-polar environment is in Table 1.

Table 1. The alloy composition of Al7075 and the new alloy, modified from [2]

Weight(%)	Mg	Zn	Cu	Si	Fe	Mn	Cr	Ti	Al
Al7075	2.48	6.52	1.64	0.727	0.19	0.053	0.263	0.095	Bal.
Modified	6	3	1.64	0.2	0.19	0.053	0.263	0.095	Bal.

4. Processing Methods

4.1. Fast Congealing

The first stage involves melting the aluminum alloy to achieve a liquid phase. This step requires precise temperature control to ensure complete melting and impurity removal. The alloy is typically heated in a furnace to approximately 660 °C (1220°F), adjusted according to the specific alloy composition. After melting, the aluminum is rapidly cooled to solidify quickly. This rapid congealing process helps to refine the grain structure of the alloy, resulting in smaller grains that enhance the mechanical properties of the tube. Techniques like water quenching or controlled air cooling are used for this purpose.

4.2. HFQ Process and Supersaturated Solid Solution

The HFQ process consists of three main stages. First, solution Heat Treatment: The aluminum alloy is heated to a high temperature to dissolve solute phases and achieve a solid solution. This prepares the alloy for subsequent forming and quenching stages. Second, forming: The heat-treated aluminum is then shaped into a tube using a die. This stage is crucial for achieving the desired tube dimensions and properties. The speed and temperature used in this step will affect the microstructure of the alloy; fast cooling results in an SSSS, which increases the strength. An SSSS is a solution that contains more solute, for example small metal piece other than aluminum, than the maximum solute amount at a given temperature. With this phenomenon, the alloy will take the maximum benefit from solid solution strengthening. Third, in-die quenching: The tube is rapidly cooled while still in the die using controlled cooling methods. This in-die quenching solidifies the tube quickly, locking in the micro-structure achieved during heat treatment and forming [9].

4.3. Tube Structure for Oceanic Oil Application

For the application of offshore oil transportation, a CFDSAT is proposed, as shown in Fig. 3. This design includes an outer aluminum skin that provides corrosion resistance and structural integrity. The concrete core adds significant compressive strength and enhances the ability of the pipeline to withstand external pressure. The inner aluminum lining provides additional protection against internal corrosion and wear. Especially for oil pipelines in the ocean may be affected by ocean currents, hurricanes and other marine activities. So, large shear forces may threaten the pipeline, and there are also high requirements for the pipeline's bending resistance. Shafayat Bin Ali concluded in his experiment that the concrete can reduce most of the inward local buckling of the outer tube, which increases the flexural strength of the tube [10]. Depending on the specific requirements, engineers can choose concrete of different strengths to adapt to various situations.

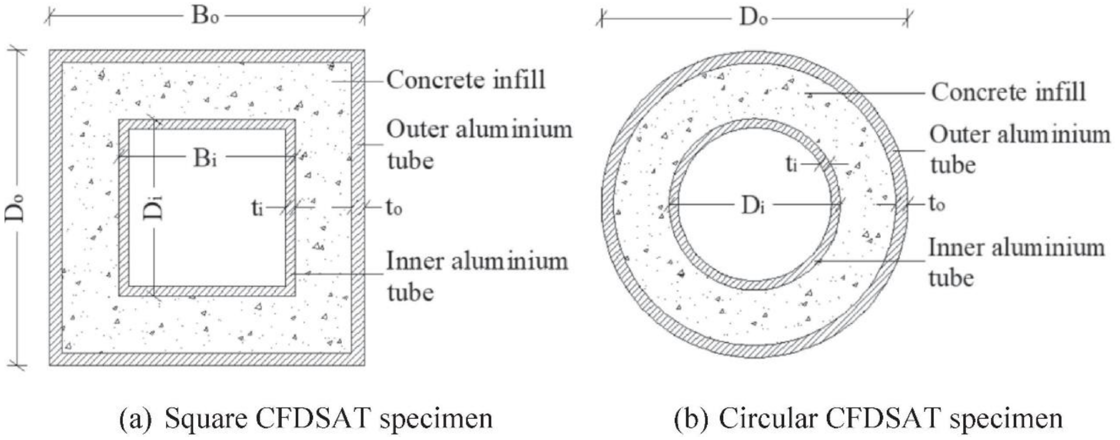

Fig. 3 Structure of the CFDSAT of different shapes [8]

4.4. Conversion Coating Process (CCP)

The CCP is one of the effective methods to improve corrosion resistance. The process of conversion coating is shown in Fig. 4.

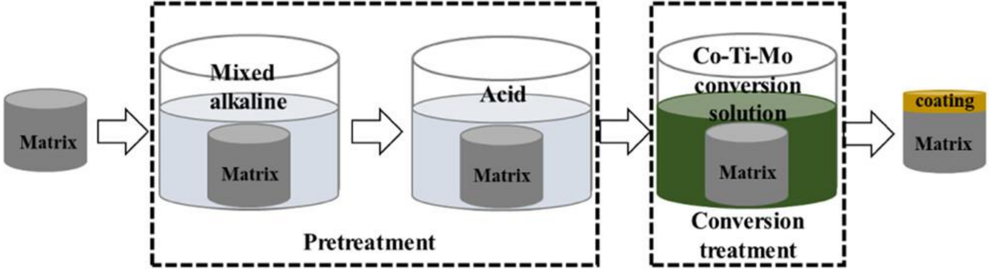

Fig. 4 Process of Co-Ti-Mo CCP

Previously, the mainstream aluminum alloy CCP in the industry was chromate CCP. However, the $Cr6^+$ in this process is highly toxic and poses a great threat to the environment [11]. Since the scenario of the application is in polar regions, the design needs special attention to environmental protection. Recently, a new type of Co-Ti-Mo Conversion Coating has been developed because of its environmental protection characteristics and stronger corrosion resistance than chromate CCP. According to Qian, the aluminum alloy, after coating, will enhance the corrosion resistance by at least five times. Qian also proposes a new formula for the conversion solution, as shown in Table 2 [11].

Table 2. The formula for the Co-Ti-Mo conversion solution [10]

$CoSO_4·7H_2O$ (g/L)	H_2TiF_6 (ml/L)	$Na_2MoO_4·2H_2O$ (g/L)	$(NaPO_3)_6$ (g/L)
2.0	1.5	1.0	0.4

5. Conclusion

An aluminum alloy to be used in oil pipelines in polar/subpolar regions has been examined. In this paper, a new alloy modified from Al7075 is proposed in order to improve its corrosion resistance, low-temperature toughness and strength. The paper concludes with the findings in binary alloy of aluminum with copper, magnesium, and zinc. With the consideration of the affection of silicon in corrosion resistance, the newly designed aluminum alloys are expected to meet the necessary standards of strength, toughness, and corrosion resistance for polar applications while continuously optimizing microstructural features and processing methods to achieve the desired comprehensive performance. The research also confirms that the proposed aluminum alloy processing method and tube structure are highly suitable for oceanic oil transportation. First, the processing steps, including melting, rapid congealing, and the HFQ process, effectively produced aluminum alloy tubes with refined grain structures and improved mechanical properties. Microscopic analysis confirmed the reduction in grain size and uniformity in the tube walls, contributing to enhanced strength and durability. Second, the proposed concrete-filled double-skin tube structure demonstrated several advantages for oceanic oil applications, which include increased strength, corrosion resistance, and flexibility. The concrete core significantly boosts the structural capacity, making the tube well-suited to withstand high pressures and marine forces. The aluminum skins provide adequate protection against corrosive marine environments. The design allows for adaptability to various dimensions and environmental conditions, offering versatility in application. For pit corrosion, which usually occurs in ocean environments, the conversion coating process can efficiently prevent pit corrosion. With the newly developed Co-Ti-Mo CC technique, the tube can reach a high corrosion resistance of 5 times higher than the original alloy. At the same time, the new technique proves that the tube is environmentally friendly.

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