Optimized Design of 7075 Aluminum Alloy for Polar Region Pipeline Applications: Composition, Processing, and Performance

Jialin Li *

School of Material Science and Engineering, Shanghai University, Shanghai, 200444, China

* Corresponding Author Email: hait@shu.edu.cn

Abstract. As traditional resource deposits dwindle, exploration efforts are increasingly shifting towards polar regions, where harsh environmental conditions demand materials with superior durability. Pipeline transportation plays a vital role in efficiently transferring resources in these extreme environments, driving the need for enhanced materials. This study focuses on optimizing the 7075 aluminum alloy to meet the specific demands of polar region pipelines. By refining its chemical composition, advancing processing techniques, and improving overall performance, the research aims to significantly enhance the alloy strength, low-temperature toughness, and corrosion resistance. Key innovations include the strategic addition of alloying elements, improved manufacturing processes, and the implementation of advanced strengthening mechanisms. These modifications are tailored to boost the material's performance under the unique conditions of polar regions, ensuring reliability and longevity in pipeline applications. The study's findings offer valuable insights into the development of materials suited for resource exploration in extreme environments, promoting sustainable infrastructure in polar areas.

Keywords: 7075 aluminum alloy, low-temperature performance, polar region pipeline.

1. Introduction

As human society continues to advance, the strain between resource depletion and regional development has become a pressing issue on a global scale. So, to address the increasing demands for sustainable growth, attention has turned to polar regions. As one of the most critical methods for transporting within these regions, pipeline transportation has far-reaching economic and strategic impacts. Given the importance of this method, the materials used in pipeline construction must meet the rigorous demands of the polar environment, particularly in terms of low-temperature performance.

Traditional materials such as steel, while widely used in pipeline construction, face significant limitations when exposed to extreme cold environments. Low temperatures can severely impact steel's mechanical properties, leading to brittleness and failure. In contrast, aluminum alloys, specifically 7075 aluminum, offer a promising alternative. They exhibit a "dual enhancement effect" in which their yield strength, tensile strength, and toughness get improved simultaneously as temperatures drop. This makes them well-suited for the demanding conditions of polar environments.

Furthermore, 7075 aluminum alloy has the added advantage of superior corrosion resistance. When exposed to the atmosphere, aluminum rapidly forms a dense, protective oxide layer that shields the material from corrosive elements, including acidic substances in the polar environment. This corrosion resistance further enhances the alloy's suitability for long-term use in polar pipelines, where exposure to harsh conditions is constant.

This paper focuses on the analysis of 7075 aluminum alloy and its application in pipeline systems for polar regions. By optimizing the alloy's chemical composition and refining processing techniques, this study seeks to enhance the material's performance under extreme conditions. A thorough evaluation of the alloy's low-temperature properties will be conducted to determine the feasibility of using 7075 aluminum alloy as a primary material for polar pipelines. Ultimately, the goal is to develop an optimized pipeline solution that not only withstands the severe conditions of polar regions but also contributes to the efficient and sustainable development of these areas. This solution could play a key role in enabling future exploration and extraction in some of the most challenging environments on the earth.

2. 7075 Aluminum Alloy in Pipeline Applications

2.1. Composition and Microstructure

The 7075 aluminum alloy, as a typical high-strength Al-Zn-Mg-Cu alloy, is currently one of the most widely used aluminum alloys in commercial applications. The 7075 aluminum alloy contains significant amounts of Zn, Mg, and Cu, and in addition to its lightweight properties, it possesses high strength and good toughness, along with excellent fatigue resistance and machinability [1]. As a result, this material has rapidly developed and gained popularity in the transportation sector.

The addition of Zn alone in the 7075 aluminum alloy provides a limited improvement in the overall strength of the material. Furthermore, it increases the susceptibility to stress corrosion within the material, raising the risk of cracking and failure. However, with the addition of Mg, a strengthening phase of MgZn2 is formed, which significantly enhances the alloy's strength. By controlling the ratio of Zn to Mg at 2.7, the material's resistance to stress corrosion can be maximized. The addition of Cu is intended to achieve solid solution strengthening. Moreover, the precipitation of CuAl2 during aging further improves the overall strength of the material [2]. Through the addition of Zn, Mg, and Cu to Al, the 7075 aluminum alloy forms an Al-Zn-Mg-Cu system, which greatly enhances the strengthening effect of the material.

2.2. Processing Techniques

The traditional manufacturing processes of 7075 aluminum alloy mainly include casting, forging, and extrusion. Based on the temperature during the production process, extrusion can be further classified into cold extrusion and hot extrusion. Cold extrusion involves placing the workpiece in liquid nitrogen for some time to cool it thoroughly, followed by immediate extrusion and cutting. During this process, liquid nitrogen is continuously sprayed onto the cutting area, ensuring the entire process is carried out at low temperatures [3]. Hot extrusion, on the other hand, involves cold pressing thin strips into billets, which are then heated in a resistance furnace. After maintaining the temperature for a set period, the billets are quickly placed into an extrusion die at the same temperature and extruded with a specific extrusion ratio [4]. In addition to these methods, rheo-casting can also be used for material preparation. This process involves melting the alloy, refining and degassing it, followed by rapid cooling to achieve uniform solidification. The remaining semi-solid slurry is then poured into a die-casting machine for rheo-casting to obtain the desired material [5].

Beyond traditional manufacturing processes, various new processing methods have emerged in the field, such as fused deposition, rapid solidification, and special channel casting. The serpentine channel preparation method involves melting the alloy, holding it at a certain temperature, and then controlling the melt to a predetermined temperature before casting through a serpentine channel, followed by complete cooling of the material [6]. Similarly, the inverted conical channel preparation involves pouring the molten alloy into an inverted conical channel for casting [7]. Rapid solidification preparation is a process where aluminum alloy, after the removal of oxides, is melted in a vacuum environment. Argon gas is then introduced, and the pressure difference between the chamber and the tank is used to eject the molten aluminum alloy. It is then sprayed onto a cold copper wheel for rapid cooling and ejected again by the wheel, resulting in an aluminum alloy with extremely fine grain size [4].

2.3. Mechanical Properties

According to the Hall-Petch equation, there is an inverse relationship between grain size and material strength: the finer the grain size, the higher the strength of the material, and vice versa. The $MgZn_2$ phase, as a critical precipitate phase in 7075 aluminum alloy, significantly enhances the material's strength. As shown in Table 1, the experimental results indicate that as the temperature increases, the grain size of the 7075 aluminum alloy also increases, and the $MgZn_2$ phase is present in the matrix. However, when the temperature rises further, the grain size decreases, accompanied by the disappearance of the $MgZn_2$ phase. Thus, the theoretical predictions align with the actual data. Additionally, observations of the fracture surfaces in Fig. 1 reveal that at lower temperatures, there are clear cleavage facets on the fracture surface, while at higher temperatures, a large number of dimples appear. This indicates that the fracture mode transits from brittle to ductile fracture, and the material's ductility is significantly improved [8].

Table 1. Mechanical properties of 7075 Al alloy at different temperatures [8]

Temperature ℃	Yield Strength MPa	Tensile Strength MPa	Breaking Elongation %
250	498^{+9}_{-6}	561^{+4}_{-6}	$16.0^{+0.2}_{-0.4}$
300	489^{+8}_{-14}	548^{+6}_{-3}	$15.5^{+0.3}_{-0.5}$
350	453^{+12}_{-10}	521^{+1}_{-5}	$12.1^{+0.2}_{-0.2}$
400	505^{+11}_{-9}	570^{+5}_{-3}	$16.9^{+0.5}_{-0.4}$

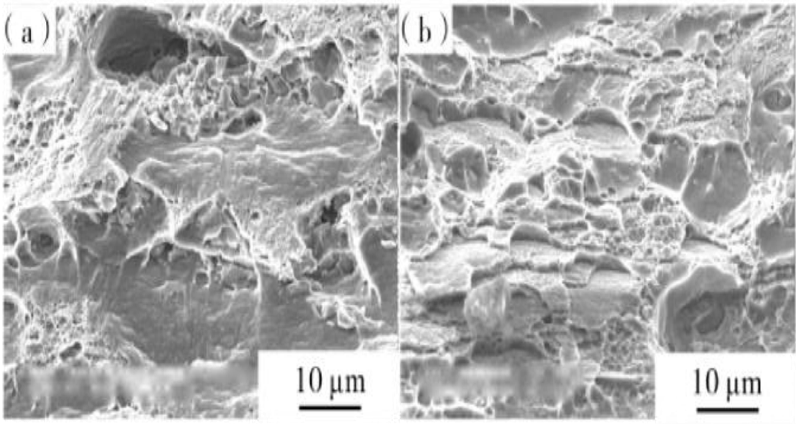

Fig. 1 Tensile fracture surface of 7075 Al alloy at different temperatures [8]

3. Optimization of Alloy Composition

The Al element is typically alloyed with additive elements such as Mg, Cu, and Zn. Among them, binary alloys like Al-Mg, Al-Cu, and Al-Zn each have their respective advantages and disadvantages, making them more specialized and less suitable for use as pipes in polar regions. Therefore, the design of multi-component alloys has emerged as a potential approach to integrate and optimize the properties of these materials [1]. 7075 aluminum alloy is designed based on the alloying of four main metal elements: Al, Zn, Mg, and Cu. In this alloy, Mg can suppress intergranular corrosion, significantly improving corrosion resistance when present in lower concentrations. Cu acts as the primary solute element within the alloy, significantly enhancing the mechanical properties of the material. Zn primarily interacts with Mg to form precipitates, contributing to the strengthening effect that improves the alloy's overall mechanical performance [2].

By leveraging the complementary effects of these elements on the overall properties, 7075 aluminum alloy exhibits several advantages, including high strength and corrosion resistance, which largely meet the requirements for service in extreme environments. However, in terms of low-temperature toughness, 7075 aluminum alloy has yet to fully meet the standards for applications in polar regions. Therefore, the optimization in this study aims to improve certain low-temperature properties of 7075 aluminum alloy, enabling it to better meet the service requirements in low-temperature environments.

The low-temperature performance of 7075 aluminum alloy can be improved by adding Sc or Li elements to the material. Sc can form nanoscale precipitates that strengthen the microstructure and enhance the low-temperature properties of the material. Li refines grains in a solid solution, improving the alloy's toughness at low temperatures and suppressing the formation of precipitates, thereby enhancing fracture toughness. Additionally, the addition of rare earth elements such as La or Ce can also form intermetallic compounds with Al, inhibiting crack propagation and improving the alloy's low-temperature toughness. In designing aluminum alloys for polar regions, in addition to low-temperature toughness, considerations must be given to cost factors and processability to ensure higher production feasibility. Therefore, besides Zn and Mg, which are already present in 7075 aluminum alloy, an appropriate amount of Li can be added to significantly improve the low-temperature performance. However, it should be noted that the addition of Zn, Mg, and Li can lead to the formation of anodic or anodic precipitates, reducing the overall corrosion resistance. Hence, a certain amount of Cr should be added to form a stable oxide film that inhibits corrosion and extends the material's service life.

4. Advancements in Processing Techniques

The traditional processing techniques for 7075 aluminum alloy have not considered its service conditions in extreme environments, so this optimization focuses primarily on the alloy's service conditions in polar regions. Aluminum alloy pipes used in polar regions need to possess high strength and toughness, along with good corrosion resistance. Therefore, the optimization plan emphasizes grain refinement in terms of the processing technique. The deep cryogenic extrusion cutting process used to prepare 7075 aluminum alloy produces ultrafine grains, which aligns with the objectives of this optimization. In this process, the solution-treated workpiece is placed in liquid nitrogen for sufficient cooling and is then quickly removed and subjected to extrusion cutting. During the processing, liquid nitrogen is continuously sprayed onto the work area, ensuring that the entire process is conducted at low temperatures [3]. Experiments have shown that the grains in the aluminum alloy are significantly refined after extrusion cutting, providing excellent corrosion resistance, and the high dislocation density within the material results in improved strength and toughness. After aging treatment, a large number of dispersed phases precipitate inside the material, while the grain size remains almost unchanged, further enhancing the material's strength. However, due to the effects of work hardening, the material's plasticity decreases significantly, along with the fracture mode transitions from the tough fracture of the solution-treated state to cleavage fracture [3]. To address this, trace amounts of RE elements can be added to reduce the dendrite spacing, refine the grains, and form intermetallic compounds with Al, improving the toughness of the material.

5. Service Performance

5.1. Strength

To enhance the strength of 7075 aluminum alloy from the perspective of strengthening mechanisms, in addition to grain refinement, three commonly used strengthening methods can be applied: solid solution strengthening, work hardening, and second-phase strengthening. All three approaches improve the overall strength of the material by impeding dislocation movement. The key difference is that solid solution strengthening introduces smaller atoms, such as Li, into the 7075 aluminum alloy to form an interstitial solid solution, which hinders dislocation motion. Second-phase strengthening utilizes the precipitation of dispersed phases, such as the $MgZn_2$ phase, within the matrix to restrict dislocations. In contrast, work hardening enhances strength by the proliferation of dislocations during deformation, which in turn suppresses dislocation movement. These three methods can significantly enhance the strength of the material, and their corresponding strategies are reflected in the compositional design and processing techniques.

5.2. Fatigue Resistance

Improvements in the fatigue performance of 7075 aluminum alloy can be achieved by adding micro-alloying elements. Adding trace amounts of Ti or Zr to the material can form plate-like precipitates within the matrix that resist the propagation of fatigue cracks, thereby enhancing the material's low-cycle fatigue performance. The addition of Mo can also be employed to suppress the formation of brittle plate-like intermetallic compounds, which not only increases the fatigue limit of the material but also improves its overall mechanical properties [9].

5.3. Corrosion Resistance

Several methods can be used to enhance the corrosion resistance of 7075 aluminum alloy, including the addition of corrosion-resistant elements, improvements in heat treatment processes, and surface treatments. Considering that various elements have already been added to optimize 7075 aluminum alloy, so to minimize the antagonistic interactions between different components that may compromise performance, ultrasonic shot peening is chosen to improve the alloy’s corrosion resistance. This method enhances corrosion resistance by refining the surface grains through shot peening, increasing the material's density, and introducing residual compressive stress to it. The degree of densification varies depending on the peening power, with higher power resulting in a denser surface structure, which ultimately improves the material's corrosion resistance [10]. Typically, peening powers of 40W and 80W are available, and for this optimization, since the alloyed aluminum pipe is expected to operate under extreme conditions, the 80W power setting is chosen to ensure normal service performance in polar regions.

5.4. Other Properties

In addition to the aforementioned performance indicators, 7075 aluminum alloy must also meet the application requirements, such as adequate thermal conductivity, machinability, and sealing performance. To prevent the material from cracking or failure due to excessive localized temperature differences, 7075 aluminum alloy can be grain-refined to improve its thermal conductivity. Regarding machinability, controlling the content of Zn and Mg in the matrix can improve the material's final cutting and forming properties. For sealing performance, surface treatment techniques such as anodizing or coating with polishing can also be employed to further enhance it.

6. Conclusion

This paper focuses on the optimization of 7075 aluminum alloy pipelines for polar applications, addressing improvements in composition design, processing techniques, and service performance. In terms of composition, the optimization is based on the traditional Al-Zn-Mg-Cu system of the 7075 alloys, with the addition of Li and Cr elements. These additions help refine the grain structure, which enhances the material’s low-temperature toughness while also forming a stable oxide layer that maintains high corrosion resistance. Regarding the processing techniques, the optimization employs cryogenic extrusion cutting methods, which produce ultrafine grains within the material matrix, significantly increasing the material's overall strength and toughness in low-temperature environments. Additionally, the corrosion resistance of the alloy is also notably improved through these processes.

Moreover, the optimized processing methods ensure the long-term durability of the alloy, allowing it to withstand the harsh and fluctuating environmental conditions of polar regions, such as extreme cold and exposure to corrosive elements. In terms of service performance, the paper introduces various strengthening methods for practical applications of the 7075 aluminum alloy, such as the addition of Ti or Mo elements to enhance fatigue resistance. Furthermore, the paper discusses the improvements in thermal conductivity, machinability, and sealing performance, all aimed at ensuring the reliable service life of the pipelines in polar regions. Overall, 7075 aluminum alloy, with its exceptional properties, is well-suited for low-temperature environments. Its ultra-high strength, excellent low-temperature toughness, and fatigue resistance make it highly valuable for polar transportation. As human activities in polar regions continue to expand, 7075 aluminum alloys will play an increasingly important role in this field.

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