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Investigation of The Refining Process of Aluminum Casting Alloys

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Abstract: This study examines the refining processes of aluminum alloys aimed at improving melt quality by removing impurities, dissolved gases, and non-metallic inclusions. Key methods, including flux treatment, gas purging, and chloride-based refining, were analyzed, with particular attention to the effectiveness of chloride–fluoride fluxes in reducing oxidation and enhancing melt cleanliness.

The results show that introducing fluxes using bell-type devices significantly improves refining efficiency compared to surface application. While chlorine refining is highly effective, its use is limited due to toxicity; therefore, alternative chloride-based agents such as hexachloroethane are widely applied.

The refining mechanism involves the formation of aluminum chloride bubbles that remove inclusions through flotation. Optimized refining conditions lead to improved microstructure and mechanical properties of aluminum alloys, providing a basis for more efficient and safer refining technologies.

Keywords: Alloy, melting process, aluminum alloys, refining process, flux treatment, non-metallic inclusions.

Introduction: Aluminum casting alloys are widely used in modern engineering applications due to their low density, high specific strength, good corrosion resistance, and excellent technological properties. These characteristics make them indispensable in aerospace, automotive, and structural industries, where performance and weight reduction are critical factors. However, the quality and performance of aluminum alloys are highly dependent on the purity of the melt and the control of impurities, inclusions, and dissolved gases during the melting process [1-4].

During melting, aluminum alloys are susceptible to contamination from the furnace atmosphere, charge materials, and refractory linings. In particular, hydrogen absorption and the formation of non-metallic inclusions significantly deteriorate the mechanical properties, casting quality, and structural integrity of the final products. Therefore, refining processes play a crucial role in improving melt cleanliness and ensuring the desired microstructure and performance characteristics.

Various refining techniques have been developed and applied in practice, including in-furnace refining and out-of-furnace treatment methods. Among these, flux refining, gas purging, and filtration are the most commonly used approaches. Refining fluxes, typically composed of chloride and fluoride salts, are widely utilized to remove inclusions, reduce oxidation, and protect the melt from atmospheric interaction. In addition, protective (covering) fluxes are applied to form a stable layer on the melt surface, minimizing oxidation and preventing contamination. Gas purging, often using inert gases such as argon or nitrogen, is effective in removing dissolved hydrogen and floating inclusions. Filtration techniques further enhance melt quality by physically trapping non-metallic particles [5-9].

Despite the extensive use of these refining methods, optimizing their application remains a significant scientific and technological challenge, particularly for advanced aluminum alloys. The efficiency of refining depends on various factors, including flux composition, processing parameters, and alloy system. For instance, alloys of the Al–Mg system require specific flux compositions due to their higher reactivity and oxidation tendency [10-12].

In this context, the present study aims to investigate the refining processes of aluminum alloys with particular emphasis on impurity removal mechanisms, melt purification efficiency, and their influence on the resulting microstructure and mechanical properties. The findings of this research are expected to contribute to the development of more efficient refining technologies and improved performance of aluminum-based materials.

METHODS

During the melting of aluminum alloys, both in-furnace refining and various external (out-of-furnace) refining techniques are widely employed to improve melt quality. Among these, the most commonly utilized methods include treatment with refining fluxes and modifying additives, gas purging, and filtration. In certain cases, electroflux refining is also applied to achieve a higher degree of purification.

The chemical compositions of the applied fluxes are summarized in Table 1, all of which are primarily based on chloride and fluoride compounds. To prevent undesirable interactions between the molten metal and the furnace atmosphere, protective (covering) fluxes are employed. These fluxes must exhibit low density, minimal hygroscopicity, the ability to form a uniform and continuous layer over the melt surface, and ease of separation during slag removal [13].

Protective fluxes are introduced into the furnace simultaneously with the charging materials. For most aluminum alloys, excluding those belonging to the Al–Mg system, fluxes No. 1–3 are typically used. In contrast, for Al–Mg-based alloys, fluxes No. 4, 5, and 6 are recommended (see Table 1).

Table 1. Chemical compositions of fluxes used in aluminum alloy melting

№	Component content (wt.%)						
	$NaCl$	KCl	Na_2AlF_3	CaF_2	MgF_2	$MgCl_2$* KCl	NaF
1	45	55	-	-	-	-	-
2	37	50	6,6	6,4	-	-	-
3	35	50	15	-	-	-	-
4	-	-	-	-	-	100	-
5	-	-	-	15	-	85	-
6	-	-	-	-	15	85	-
7	30	47	23	-	-	-	-
8	-	-	-	40		60	-
9	-	-	-	-	15	85	-
10	47,5	47,5	5	-	-	-	-
11	35	40	10	-	-	-	15
12	56,5	11,5	7	-	-	-	25
13	50	10	10	-	-	-	30

Refining fluxes (No. 7–11, Table 1) can be introduced directly onto the surface of the melt in a ladle or in the crucible of a holding furnace. However, this method is relatively inefficient, as in such conditions they primarily act as covering fluxes, providing only partial refinement of the melt.A more effective approach involves introducing the flux into the melt using a bell-type device. For example, fluxes No. 10 and 11 (Table 1) are introduced in liquid form by means of a bell (flux injection device), which enhances their interaction with the molten metal and improves refining efficiency. A special group is represented by universal fluxes (No. 12 and 13, Table 1), the use of which allows the simultaneous combination of refining and modification of the alloy. These fluxes typically contain sodium fluoride (NaF), whose presence accounts for the modifying effect. The content of NaF in such fluxes can reach up to 60 wt.% [14].

DISCUSSION

Gas refining is carried out at a temperature of 710–730 °C for a duration of 5–20 minutes. Treatment of the melt with chlorine is an effective process; however, chlorine is highly toxic, which necessitates the use of specialized equipment for refining operations, such as sealed chambers, ladles, efficient ventilation systems, and isolated facilities. These requirements significantly limit the practical application of chlorine refining.

For this reason, in the production of shaped aluminum alloy castings, processes involving melt treatment with chlorides are widely used. Such chlorides include zinc chloride ($ZnCl_2$), manganese chloride ($MnCl_2$), hexachloroethane (C_2Cl_6), titanium tetrachloride ($TiCl_4$), and others. Due to the high hygroscopicity of chlorides, they must be thoroughly dried prior to their introduction into the melt.Chlorides are introduced into the melt using a bell-type device, as their density is relatively low. The consumption typically ranges from 0.05 to 2 wt.% of the melt mass, with processing temperatures maintained between 700 and 730 °C. In the case of hexachloroethane, the consumption ranges from 0.3 to 0.7 wt.%, and the treatment is carried out at 740–750 °C. Lower temperatures reduce the refining efficiency, whereas higher temperatures lead to intensive oxidation of the alloy. In foundry practice, tablets of the commercial preparation “Degasser,” which contain hexachloroethane and barium chloride (approximately 10 wt.%), are widely used. Hexachloroethane (C_2Cl_6) is an organic compound with a density of 2.09 × 10^3 kg/m^3 and a relatively low melting point (186.5 °C). Unlike chloride salts, C_2Cl_6 is non-hygroscopic and does not require special storage conditions.

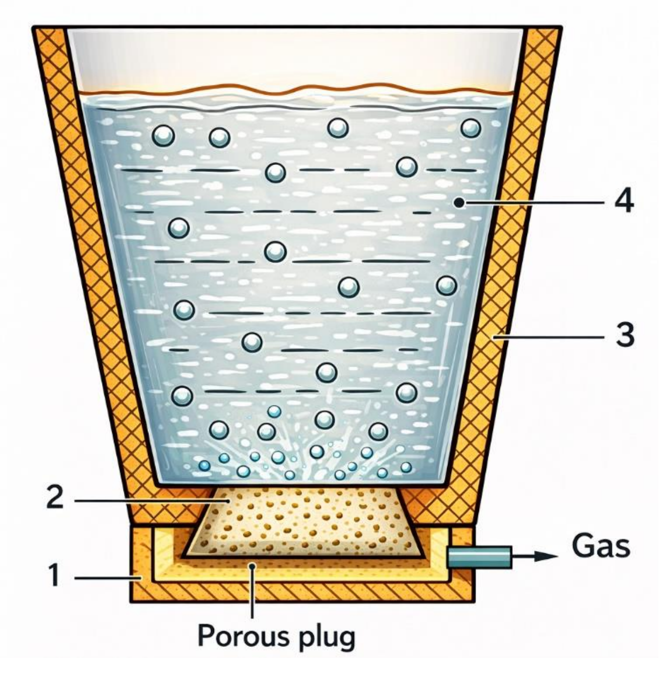

Fig. 1: Ladle with a porous ceramic insert for purging melts with an inert gas: 1-casting for supplying inert gas; 2-porous ceramic insert; 3-lining; 4-gas bubble.

In the molten state, chloride compounds chemically interact with aluminum.

$$3MeCl + 2Al \rightarrow 2AlCl_3 + 3Me.$$

Aluminum chloride, formed in the melt, rises in the form of fine bubbles and passes through the liquid metal. During this process, these bubbles effectively capture and entrain non-metallic inclusions due to interfacial interactions and flotation mechanisms. As the bubbles ascend to the melt surface, they carry the inclusions with them, resulting in their removal along with the slag layer. This mechanism significantly enhances the purification efficiency of the melt by reducing the content of oxide films and other non-metallic impurities. Consequently, the cleanliness of the aluminum alloy is improved, which has a positive effect on its microstructure, mechanical properties, and overall casting quality.

CONCLUSIONS

In this study, the refining processes of aluminum alloys were systematically analyzed with particular emphasis on flux treatment, gas refining, and chloride-based purification methods. The results demonstrate that melt quality is strongly influenced by the selection of refining techniques, processing parameters, and flux compositions. It was established that conventional flux refining, when applied only on the melt surface, provides limited efficiency, whereas deeper introduction of fluxes using bell-type devices significantly enhances refining performance. The use of universal fluxes containing sodium fluoride (NaF) allows the simultaneous achievement of refining and modification effects, improving the overall properties of the alloy. Gas refining, particularly with chlorine, was shown to be highly effective in removing impurities; however, its practical application is restricted due to toxicity and stringent safety requirements. As an alternative, chloride-based compounds such as hexachloroethane and other metal chlorides are widely used in foundry practice. Their effectiveness depends on proper temperature control, dosage, and pre-treatment conditions such as drying. The refining mechanism is primarily associated with the formation of aluminum chloride bubbles, which rise through the melt and capture non-metallic inclusions via flotation. This process significantly reduces the content of harmful impurities, leading to improved melt cleanliness, refined microstructure, and enhanced mechanical properties of aluminum alloys. Overall, the study confirms that the optimization of refining technologies is essential for achieving high-quality aluminum alloys, and the combined application of fluxes and gas-based treatments offers the most effective approach for industrial practice.

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