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Effect of Al-TiO$_2$-C-Y$_2$O$_3$ refiner on grain size and mechanical properties of Al-5Cu alloy

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A series of new Al-TiO$_2$-C-Y$_2$O$_3$ aluminum alloy grain refiners with different Y$_2$O$_3$ content was prepared by exothermic dispersion method using Al, TiO$_2$, C, and Y$_2$O$_3$ powders as raw materials. Scanning electron microscopy (SEM), x-ray diffraction (XRD), and energy-dispersive X-ray spectroscopy (EDS) were used to investigate the effect of Y$_2$O$_3$ content on the structure of the Al-TiO$_2$-C-Y$_2$O$_3$ refiner, grain refinement effect on the Al-5Cu alloy with Si content of 3 wt% or higher. The results showed that the Al-TiO$_2$-C-Y$_2$O$_3$ refiner was composed of Al$_2$O$_3$, TiC, Al$_3$Ti, Al$_5$Y$_3$O$_12$, and Al$_{20}$Ti$_2$Y phases. The refiner with 4% Y$_2$O$_3$ content exhibited the best Al-5Cu alloy refining effect, achieving a grain size of about 210.5 μm. This was about 42% of the grain size of the original Al-5Cu alloy. Moreover, this refined Al-5Cu alloy exhibited the best mechanical properties, with a tensile strength and elongation of 173.13 MPa and 9.19% respectively. This was a 20.9% and 83.8% improvement compared with the original Al-5Cu alloy. However, with a further increase in Y$_2$O$_3$ content, an Al$_5$Y$_3$O$_12$ phase was preferentially formed. This led to a decline in Al$_{20}$Ti$_2$Y phase content and a correspondingly weaker refinement effect.

1. Introduction

Due to rapid economic development around the world, aluminum alloys are widely used in many fields such as construction, transportation, machinery manufacturing, and the aerospace industry. Many applications have increasingly demanding material requirements regarding the comprehensive properties of aluminum alloys [1–3]. The most effective and economical strategy for improving the comprehensive properties of aluminum alloys is to add a grain refiner to the aluminum alloy melt [4]. At present, Al-Ti-B refiners are usually used in industry to refine aluminum alloys. However, these Al-Ti-B refiners lead to a ‘poisoning’ phenomenon when they are used to refine aluminum alloys containing Cr, Zn, and some other elements [5]. Wang et al [6] reported that an Al-Ti-B refiner had no obvious refining effect on an aluminum alloy with Si content of 3 wt% or higher. This was mainly because the enrichment of Si at the TiB$_2$/Al-Si interface caused the Al$_3$Ti layer on the TiB$_2$ surface to dissolve into the Al-Si melt. Thus, the particle nucleation ability of TiB$_2$ was lost, resulting in a reduction in the number of cores available for heterogeneous nucleation and a corresponding increase in grain size. In recent years, scholars have developed Al-Ti-C refiners to effectively avoid the problems associated with Al-Ti-B refiners. Kumar et al [7] prepared Al-Ti-0.8C and Al-5Ti-1.2C master alloys by reacting K$_2$TiF$_6$ salt and graphite powder with molten Al at 1200 °C. They found that the refining ability of these alloys was better than that of the traditional Al-5Ti-1.2C master alloy. At the same time, the growth of Al$_3$Ti was completely inhibited in the Al-5Ti-1.2C master alloy, demonstrating its enhanced refining ability. However, during the preparation of Al-Ti-C refiners, TiC easily aggregates, the wettability between C and the Al melt is poor, and the reaction process is difficult. These drawbacks limit the development of Al-Ti-C refiners [8–10]. Therefore, Al-TiO$_2$-C refiners have been extensively studied as an alternative refiner system. In addition to Al$_3$Ti and TiC secondary
phases (the same as those of Al-Ti-C refiners). Al-TiO\textsubscript{2}-C refiners contain Al\textsubscript{2}O\textsubscript{3} particles that can impede grain growth. This improves the grain refinement effect of these refiners [11].

Many scholars have prepared new refiners by adding rare earth elements to traditional refiners, which can lead to more effective refining [12, 13]. Rare earth metals are surfactants that can be adsorbed on the surface of carbon atoms. This improves the wettability of refiners with the Al melt, thus improving refining ability [14]. However, due to the complex manufacturing process and high cost of rare earth refiners, scholars have also investigated the addition of rare earth oxides to refiners to improve their refining effect. After adding La\textsubscript{2}O\textsubscript{3} to an Al-Ti-C master alloy, Ding et al. [15] found that La\textsubscript{2}O\textsubscript{3} promoted the formation of TiC and changed the morphology of Al-Ti. Thus, the refining ability of Al-Ti-C was improved. According to the above studies, the final reaction products of Al-TiO\textsubscript{2}-C refiner include Al\textsubscript{3}Ti, TiC and Al\textsubscript{2}O\textsubscript{3} phases, which are similar to the phase composition of Al-Ti-C grain refiner, and its refining effect can be improved through some special processes and methods, which has good development prospects. However, research on the addition of rare earth oxides to refiners is relatively limited. Thus, in this paper, an Al-TiO\textsubscript{2}-C-Y\textsubscript{2}O\textsubscript{3} refiner was prepared by exothermic dispersion method, and the refining effect of Al-TiO\textsubscript{2}-C refiner was enhanced by adding the rare earth oxide Y\textsubscript{2}O\textsubscript{3}. The effect of Y\textsubscript{2}O\textsubscript{3} content on the structure of the Al-TiO\textsubscript{2}-C refiner will be the focus of this study.

2. Experimental procedure

Al powder (99.9%), TiO\textsubscript{2} powder (99.9%), C powder (99.9%), and rare earth oxide Y\textsubscript{2}O\textsubscript{3} powder (99.9%) were evenly mixed in a certain proportion. Y\textsubscript{2}O\textsubscript{3} mass fractions of 0, 2%, 4%, 6%, 8% were used. The TiO\textsubscript{2} content was 12% and the Ti:C ratio was 10:1. The mixed powder was ground in a planetary ball mill for about 1 h. After grinding, the ground powder was loaded in a universal testing machine, then pressed into a cylindrical preform. A pressure rise rate of 800 N s\textsuperscript{-1} was used, and the preform was pressed at 90 kN for 180 s. After pressing, the precast block was placed into a corundum crucible, which was filled with Al\textsubscript{2}O\textsubscript{3} powder around the sample. The corundum crucible was placed in a drying oven for drying at 150 °C, then in a high-temperature sintering furnace for sintering. The heating rate for sintering was about 3 °C min\textsuperscript{-1}, the target sintering temperature was 1300 °C, and the dwell time was 2 h. After cooling, Al-TiO\textsubscript{2}-C refiners with different Y\textsubscript{2}O\textsubscript{3} content were obtained. X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy-dispersive x-ray spectroscopy (EDS) were used to analyze the phase and microstructure of the refiners.

Refining experiments were carried out in a crucible resistance furnace, in which the amount of refiner was 0.3 wt% (mass fraction). First, the Al-5Cu alloy and Al-TiO\textsubscript{2}-C-Y\textsubscript{2}O\textsubscript{3} refiner were weighed. The crucible was preheated in a drying oven at 200 °C for 1 h before casting. Next, the weighed alloy was added to the preheated crucible in batches, and the loaded crucible was placed in a crucible resistance furnace at 750 °C for 45 min to melt the alloy. After melting, the refiner was added to the molten alloy, which was stirred with a graphite rod for 15 s. The crucible was then placed back in the crucible resistance furnace for 15 min to allow the refiner to fully react. Finally, the melt was cast into a preheated mold at 200 °C. Several 10 mm × 10 mm × 10 mm samples were cut from the same position in the center of the mold, polished step by step with sandpaper, and then mechanically polished. The polished samples were then anodized in HBF\textsubscript{4} solution. The HBF\textsubscript{4} solution concentration was 2%, the coating voltage was 25 V, the coating current was 0.1 A, and the coating time was 1–2 min. Grain sizes were observed by a polarizing microscope to determine the average grain size.

Several 10 mm × 10 mm × 10 mm samples were cut from the same position in the center of the mold, mechanically polished, and corroded with Keller’s reagent (1.3% HCl + 2.5% HNO\textsubscript{3} + 1% HF + 95% H\textsubscript{2}O). The phase composition was analyzed by X-ray diffractometer (XRD, Cu K-α, D/Max-2500/PC), the morphology was observed by scanning electron microscope (SEM, QUANTA FEG 650), and the distribution of elements was observed by energy-dispersive x-ray spectroscopy (EDS).

The formula for calculating the standard Gibbs free energy change \( \Delta G \) of a reaction is:

\[
\Delta G^\circ_T = \left( \sum_i v_i \Delta G^{\circ}_{m,i} \right)_{\text{Products}} - \left( \sum_j v_j \Delta G^{\circ}_{m,j} \right)_{\text{Reactants}}
\]

In the formula, \( \sum_i v_i \Delta G^{\circ}_{m,i} \) and \( \sum_j v_j \Delta G^{\circ}_{m,j} \) are the sum of the standard Gibbs free energy changes of the products and reactants of the reaction.

Tensile experiments were carried out on a computer-controlled electronic tensile testing machine. Plate samples fabricated according to the national standard GB6397–86 were used in the tensile tests. The sample dimensions are shown in figure 1.
3. Results and discussion

3.1. Effect of Y$_2$O$_3$ content on microstructure of Al-TiO$_2$-C-Y$_2$O$_3$ refiner

Figure 2 shows the XRD patterns of the Al-TiO$_2$-C-Y$_2$O$_3$ refiners with varying Y$_2$O$_3$ content. The secondary phases of the Y$_2$O$_3$-free Al-TiO$_2$-C refiner are mainly Al$_2$O$_3$, TiC, and Al$_3$Ti. When the rare earth oxide Y$_2$O$_3$ is added, two new rare earth phases are generated: Al$_5$Y$_3$O$_{12}$ and Al$_{20}$Ti$_2$Y. The intensity of the Al$_5$Y$_3$O$_{12}$ diffraction peak at 18.05° gradually increases with increasing rare earth oxide content. In contrast, the Al$_2$O$_3$ peak intensity gradually decreases with increasing Y$_2$O$_3$ content. It is speculated that Y$_2$O$_3$ and Al$_2$O$_3$ form the new rare earth oxide phase Al$_5$Y$_3$O$_{12}$ after the addition of Y$_2$O$_3$ to the Al-TiO$_2$-C refiner. Unfortunately, the characteristic peaks of the Al$_{20}$Ti$_2$Y rare earth phase are superimposed with the characteristic peaks of other phases. Therefore, it is difficult to determine the specific trend of Al$_{20}$Ti$_2$Y rare earth phase content with increasing Y$_2$O$_3$ addition.

Figure 3 shows SEM images displaying the microstructures of the Al-TiO$_2$-C-Y$_2$O$_3$ refiners. Two new phases are visible after the addition of Y$_2$O$_3$: a bright white bulk phase and a bright white granular phase. EDS analysis was performed to confirm the composition of these phases. Figure 4 shows the EDS analysis area of the Al-TiO$_2$-C-4%Y$_2$O$_3$ refiner and the EDS spectra of the corresponding points, it can be determined that the white plate phase (point A) is the Al$_3$Ti phase, and the bright white bulk phase (point B) is composed of three elements, Al, Ti and Y. In combination with the XRD results, the phase is identified as Al$_{20}$Ti$_2$Y phase. The dark black granular phase dispersed in the matrix (point C) is Al$_2$O$_3$ particles, and the white granular phase (point D) is composed of three elements, Al, Y and O, and the element molar ratio is close to 5:3:12. In combination with the XRD results, the phase is determined to be Al$_5$Y$_3$O$_{12}$ particles.

It can be seen from figure 3(a) that Al-TiO$_2$-C refiner is composed of Al matrix, Al$_2$O$_3$, TiC and Al$_3$Ti phase. Figures 3(b)–(e) shows the microstructure of Al-TiO$_2$-C-Y$_2$O$_3$ refiner with different contents of Y$_2$O$_3$. With increasing Y$_2$O$_3$ content, the lath-shaped Al$_3$Ti gradually transforms into a block shape. The bulk Al$_{20}$Ti$_2$Y phase
and granular Al$_5$Y$_3$O$_{12}$ phase are newly formed in the matrix. The bulk Al$_{20}$Ti$_2$Y phase increases first and then decreases. When 4% Y$_2$O$_3$ is added, the content of Al$_{20}$Ti$_2$Y phase reaches the highest, as shown in figure 3(c). The amount of Al$_5$Y$_3$O$_{12}$ gradually increases with the increase of the content of Y$_2$O$_3$. When 8% Y$_2$O$_3$ is added, a large number of granular Al$_5$Y$_3$O$_{12}$ phases are distributed in the matrix, as shown in figure 3(e), which is consistent with the XRD results.

The microscopic morphology of the refiners shown in figure 3 demonstrates that the white bulk Al$_{20}$Ti$_2$Y phase first increases and then decreases with increasing Y$_2$O$_3$ content. The highest amount of Al$_{20}$Ti$_2$Y is achieved with 4% Y$_2$O$_3$, and less Al$_{20}$Ti$_2$Y is generated with the addition of 6%–8% Y$_2$O$_3$. To determine the relative area ratio of the Al$_{20}$Ti$_2$Y phase in each sample, three SEM images of each sample obtained at the same magnification level were analyzed by simulation software. The results of this analysis are displayed in figure 5. As shown, the relative area ratio of the Al$_{20}$Ti$_2$Y phase is stable at about 6% when 2–4 Y$_2$O$_3$ is added. However, with the further addition of Y$_2$O$_3$, the surface proportion of Al$_{20}$Ti$_2$Y declines. The Al-TiO$_2$-C refiner with 8% Y$_2$O$_3$ has the lowest Al$_{20}$Ti$_2$Y relative surface area (only 3.86%). At the same time, figure 3 clearly demonstrates that the bright white granular Al$_5$Y$_3$O$_{12}$ phase gradually increases with the increasing addition of Y$_2$O$_3$.

EDS maps of the Al-TiO$_2$-C refiner with 4% Y$_2$O$_3$ are displayed in figure 6. The gray granular Al$_2$O$_3$ phase and the bright white Al$_5$Y$_3$O$_{12}$ phase are present on the Al matrix or grain boundaries. The diameter of the dispersed phases is between 2 μm and 5 μm. This is because the Al$_5$O$_3$ particles and Al$_5$Y$_3$O$_{12}$ have large particle
sizes and poor wettability with Al. These phases are distributed along the grain boundaries during the solidification process. This EDS mapping analysis also demonstrates that another rare earth phase, Al$_{20}$Ti$_2$Y, is distributed around Al$_3$Ti in a flake shape.

Figure 4. EDS analysis of Al-TiO$_2$-C-4%Y$_2$O$_3$ refiners: (a) analysis area and EDS spectra of (b) Point A; (c) Point B; (d) Point C; (e) Point D.

Figure 5. The relative area ratio of the Al$_{20}$Ti$_2$Y phase in the Al-TiO$_2$-C-XY$_2$O$_3$ refiners.
3.2. Thermodynamic and kinetic analysis of Al-TiO2-C-Y2O3 refiners

As the temperature of the reaction system rises during the melting process, the thermite reaction between Al and TiO2 occurs first. As shown in Reaction (3–1), Al and TiO2 react to form active [Ti] atoms and Al2O3, and this reaction releases a significant amount of heat.

\[
\text{Al} + \text{TiO}_2 \rightarrow \text{Ti} + \text{Al}_2\text{O}_3 \quad \Delta G = -518754 + 120.6T \text{ J mol}^{-1}
\] (3-1)

The active [Ti] atoms generated by Reaction (3–1) react with Al or C in the melt to form free Al3Ti and TiC particles, as shown in Reactions (3–2) and (3–3). As can be seen from figure 3(a), Al2O3, TiC and Al3Ti phases are generated by Reactions (3–1)–(3–3).

\[
\text{Ti} + \text{Ti} \rightarrow \text{Al}_3\text{Ti} \quad \Delta G = -146400 + 32.6T \text{ J mol}^{-1}
\] (3-2)

\[
\text{Ti} + \text{C} \rightarrow \text{TiC} \quad \Delta G = -184000 + 12.1T \text{ J mol}^{-1}
\] (3-3)

As the temperature of the reaction system continues to rise, heat continues to be released by Reactions (3–1)–(3–3). The Gibbs free energy of the reaction of Y2O3 with reducing C is \(\Delta G = -1132800 + 739T \text{ J mol}^{-1}\). When \(T > 1532 \text{ K}\), the Gibbs free energy is less than 0 and Reaction (3–5) proceeds spontaneously. However, it has been reported that Y2O3 reacts with Al2O3 to form a Y4Al2O9 phase at 900 °C–1100 °C. As the temperature continues to rise, Y4Al2O9 reacts with Al2O3, and the Al5Y3O12 phase is finally formed [16]. Reaction (3–4) occurs before Reaction (3–5) and consumes a large quantity of Al2O3 particles. This is corroborated by the weakening XRD peak intensity of Al2O3 with increasing Y2O3 content, as shown in figure 2. As can be seen from figures 3(b)–(e), an increasing number of Al5Y3O12 phases are generated from Y2O3 and Al2O3 particles by Reaction (3–4). The YC2 produced by Reaction (3–5) is not stable at high temperatures and reacts with free [Ti] atoms to form TiC particles and rare earth [Y] atoms. The rare earth [Y] atoms are more active and react with the Al3Ti produced by Reaction (3–2) to form another stable rare earth phase, Al20Ti2Y, as shown in Reactions (3–6) and (3–7). As can be seen from figure 3(c) that the rare earth [Y] atoms and Al3Ti form the Al20Ti2Y phase by Reaction (3–7), and the Al20Ti2Y phase is distributed around Al3Ti in a flake shape.

\[
3\text{Y}_2\text{O}_3 + 5\text{Al}_2\text{O}_3 \rightarrow 2\text{Al}_3\text{Y}_2\text{O}_{12}
\] (3-4)

\[
\text{Y}_2\text{O}_3 + \text{O}_2 + 9\text{C} \rightarrow 2\text{YC}_2 + 5\text{CO(g)}
\] (3-5)

\[
\text{YC}_2 + 2\text{[Ti]} \rightarrow 2\text{TiC} + \text{[Y]}
\] (3-6)

\[
\text{[Y]} + \text{Al}_3\text{Ti} + \text{Al} \rightarrow \text{Al}_{20}\text{Ti}_2\text{Y}
\] (3-7)

When Y2O3 is added to the Al-TiO2-C refiner, the rare earth phase Al3Y2O12 is preferentially formed and a large amount of Y2O3 particles are consumed during the reaction. This inhibits Reaction (3–7), resulting in lower Al20Ti2Y generation.

3.3. Refining effect of Al-TiO2-C-Y2O3 refiner on Al-5Cu alloy

Figure 7 shows polarized images of Al-5Cu alloys obtained after adding Al-TiO2-C-Y2O3 refiners with varying Y2O3 content. The original coarse grains of Al-5Cu, as shown in figure 7(a), gradually become finer with the
addition of refiners with increasing $\text{Y}_2\text{O}_3$ content. The best refining effect is achieved with 4% $\text{Y}_2\text{O}_3$, as shown in figure 7(c). If the content of $\text{Y}_2\text{O}_3$ is increased above 4%, as shown in figure 7(d)–(e), the grain size becomes coarser again. Figure 7(f) shows the average grain size of these alloys. The grain size of the unre fined $\text{Al}-5\text{Cu}$ alloy is about 500 $\mu$m. The addition of the $\text{Al}-\text{TiO}_2-\text{C}$ refiner containing 4% $\text{Y}_2\text{O}_3$ leads to an alloy with a grain size of about 210.5 $\mu$m. This is only 42% of the grain size of the original $\text{Al}-5\text{Cu}$ alloy. However, this refining effect is not improved by further increasing the $\text{Y}_2\text{O}_3$ content.

In general, the grain size during solidification dependent mostly on the heterogeneous nucleation of the solid phase and the subsequent growth of the newly formed nuclei [17]. The secondary phases of the $\text{Al}-\text{TiO}_2-\text{C}-\text{XY}_2\text{O}_3$ alloys prepared in this work are mainly $\text{TiC}$, $\text{Al}_2\text{Ti}$, $\text{Al}_2\text{O}_3$, $\text{Al}_2\text{O}_3\text{Ti}_2\text{Y}$, and $\text{Al}_2\text{Y}_3\text{O}_{12}$. The $\text{TiC}$ crystals have a face-centered cubic structure, which is the same as the crystal structure of aluminum. Moreover, the lattice constants of these two phases are relatively similar, and they both exhibit good stability at high temperatures and can be used as an excellent substrate for heterogeneous nucleation. However, related studies [18] have found that $\text{TiC}$ particles are too small to be used as heterogeneous nucleation cores for effective grain
refinement. After the Al-TiO₂-C-XY₂O₃ refiner enters the Al-5Cu alloy melt, the unstable Al₂₀Ti₂Y and Al₃Ti phases dissolve, releasing a large amount of free Ti and Y atoms. The Ti atoms accumulate on the surface of TiC, forming a Ti-rich layer. These particles become heterogeneous nucleation cores that effectively refine the crystal grains and improve the nucleation ability of the alloy. The Ti-rich layer can prevent TiC from being poisoned by the formation of Al₅C₃ or may form constitutional supercooling, hampering grain growth and playing a wonderful refinement in the solidification processing [15, 19]. As active rare earth particles, Y atoms improve the wettability of TiC and Al, and improve the nucleation ability of α-Al [20], enhancing grain refinement.

Al₃Ti can be directly used as heterogeneous nucleation cores for refining grains. The morphology and quantity of Al₃Ti particles are key factors that influence the effectiveness of the Al-TiO₂-C-XY₂O₃ refiners. When the Y₂O₃ content is low, Al₃Ti appears as coarse laths and the nucleated grains are abnormally coarse; with increasing Y₂O₃ content, the lath-shaped Al₃Ti gradually transforms into a block shape. The block-shaped Al₃Ti easily dissolves at the reaction system temperature and releases a large amount of free Ti atoms, leading to the formation of a Ti-rich layer that wraps the TiC particles. At the same time, a small amount of undissolved Al₃Ti will act as nucleating agent to form α-Al. This promotes the non-uniform nucleation of α-Al and refines the alloy grains [21].

Al₂O₃ has a large particle size and poor wettability with Al. The Al₂O₃ particles are distributed along the grain boundary during the solidification process, hindering the growth of grains and enhancing grain refinement [22].

The dissolution of Al₂₀Ti₂Y at high temperature not only releases a large number of free Ti atoms, but also generates a small number of Y atoms. Related studies [23, 24] have shown that Y atoms will converge on the solid-liquid interface in the solidification process of the alloy, which reduces the tension of the solid-liquid interface, affects the solute redistribution in the solid-liquid front, causes the concentration gradient of the liquid phase in the solid-liquid front, forms the component undercooling, improves the nucleation rate, and refines the grain size.

The Al-TiO₂-C-XY₂O₃ refiner preferentially generates the Al₅Y₃O₁₂ rare earth phase during the preparation process. This Al₅Y₃O₁₂ phase has a larger particle size. However, this impurity phase has no obvious effect on Al-Cu alloy refinement. The formation of the Al₅Y₃O₁₂ phase consumes a large amount of rare earth Y, resulting in a significant reduction in the content of the Al₂₀Ti₂Y rare earth phase, which has a better refinement effect. When 8% Y₂O₃ is added, the relative area ratio of the Al₂₀Ti₂Y phase in the refining agent is only 3.8%. This is also the main reason why the excessive addition of Y₂O₃ inhibits the refining effect.

3.4. Effect of Al-TiO₂-C-Y₂O₃ refiner on mechanical properties of Al-5Cu alloy
The tensile strength and elongation of the Al-5Cu alloys obtained using the Al-TiO₂-C-XY₂O₃ refiners are shown in figure 8. The tensile strength and elongation of the unrefined Al-5Cu alloy are 143.2 MPa and 5.0%, respectively. The addition of Al-TiO₂-C-XY₂O₃ refiners with increasing Y₂O₃ content significantly enhances the tensile strength and elongation of the Al-5Cu alloy up to 4% Y₂O₃. The highest tensile strength and elongation, 173.13 MPa and 9.19%, are achieved with 4% Y₂O₃. Compared with the original Al-5Cu alloy, this represents an enhancement of 20.9% and 83.8%, respectively. However, further increasing the Y₂O₃ content leads to a reduction in the tensile strength and elongation of the Al-5Cu alloy.
4. Conclusion

(1) The secondary phases of the Al-TiO₂-C refining agent are mainly Al₂O₃, TiC, and Al₅Ti. After adding Y₂O₃, an Al₁₂₀Ti₂Y rare earth phase and an Al₁₂₇Y₃O₁₂ rare earth phase are formed. The Al₁₂₀Ti₂Y rare earth phase has an important role in grain refinement. However, the Al₁₂₇Y₃O₁₂ phase, which does not improve grain refinement, is preferentially formed. The excessive addition of Y₂O₃ reduces the Al₁₂₀Ti₂Y phase content of the alloy, leading to an inhibited refining effect.

(2) The Al-TiO₂-C refining agent shows the best aluminum-copper alloy refining effect with 4% Y₂O₃. The addition of the Al-TiO₂-C-4%Y₂O₃ refiner to an Al-5Cu alloy leads to grain refinement from about 500 μm to about 210.5 μm. This refining effect represents a 42% reduction in grain size compared to the original Al-5Cu alloy.

(3) The mechanical properties of the tested aluminum-copper alloys are significantly improved by the addition of the Al-TiO₂-C-X₄Y₂O₃ refiners. The addition of the Al-TiO₂-C-4%Y₂O₃ to the Al-5Cu alloy leads to tensile strength and elongation values of 173.13 MPa and 9.19%, respectively. This represents a 20.9% and 83.8% enhancement compared with the tensile strength and elongation of the original Al-5Cu alloy.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

The authors declare that they have no conflict of interest.

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