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Strengthening mechanism of Sr element on 6063 Al alloys

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Abstract

The micro-texture, grain size, morphology, size and distribution of the second phase in 6063 Al alloys significantly influence the comprehensive mechanical properties of alloys. By adding Sr to the 6063 Al alloys, this study performed a comparison of the effect exerted by micro-texture and grain refinement and explored the existence of Sr and its influence on the second phase. In addition, the influence mechanism for mechanical properties of the Sr-added alloys was also investigated. The results show that the phase structure of 6063 Al alloys is changed after adding Sr. The Al2Si2Sr intermetallic compound is formed, and numerous substructures are developed during dynamic recovery and recrystallization. Moreover, after adding Sr element, the grain size of 6063 Al alloys is reduced from 33.45 μm to 24.04 μm. Small-angle grain boundaries increase, while large-angle grain boundaries decrease. Sr element changes the micro-texture of 6063 Al alloys significantly when Cube {100} {001}, Goss {1 10} {001} and S {1 23} {634} become Cube {100} {001}. The tensile strength, yield strength and Brinell hardness of 6063 Al alloys increase by 59.67%, 69.36% and 36.63%, respectively. Taken together, the Sr element strengthens the mechanical properties of 6063 Al alloys through fine-grained strengthening.

1. Introduction

The 6063 Al alloys have been widely used as a building material in recent years, featured by lent formability and extrusion, medium strength, good processability and satisfying corrosion resistance [1]. They are also extensively employed in the manufacturing of automobiles and mobile phones, aerospace, and other fields [2, 3]. Grain refinement is commonly used for alloy strengthening and is also one of the most effective methods to improve the toughness of aluminum alloys [4]. In the existing industrial production, 6063 Al alloys are refined by the master alloy, such as Al-Ti-B master alloy. The 6063 Al alloys refined with Ti, Ti+RE or Ti+RE + Ball represent better aging behavior [5]. Ding et al [2] revealed that adding the rare-earth Y combined with Al-Ti-B master alloy decreased the grain sizes of 6063 Al alloys. Rare earth Y is mainly distributed among TiB2 particles in the form of AlTiY particles, and part of it exists on α-Al grains of in the form of Al3Y. The 6063 Al alloys are a precipitation hardening alloy with the main elements of Mg and Si [6]. Reinforced particles such as boron oxides, borides, nitrides, carbides, ceramic particles, nanoparticles and W are embedded in the α-Al base, which increases the tensile strength but slightly reduces plasticity [7–10].

However, although these alloy elements and reinforcing particles can refine α-Al [11], they have minimal influence on the second phase, such as Mg2Si particles. Thus, it is urgent to seek an effective method to enhance the overall performance of 6063 Al alloys. Through these methods, the grain size of α-Al in 6063 Al alloys is refined, and the shape, size, and distribution of the second phase are optimized. The grain-refining effect of Sr, as a refining agent of Al–Mg–Si alloy, has been proved during metal solidification in many studies of different research fields [12–14]. Lin et al [14] found that adding Sr can obtain the best spheroidized and refined eutectic Si particles after approximately 2-h solution treatment. Qin et al [15] reported that the poisoning effect of Sr on
Mg$_2$Si crystals in Al-Mg-Si melt is the responsible mechanism for the morphology transformation of Mg$_2$Si crystals. Ghandvar et al.\cite{16} revealed that the Al$_5$Ba compound can act as the nucleus for the primary Mg$_2$Si during solidification, leading to the refining of the primary Mg$_2$Si particle size extensively. To sum up, these studies mainly improve the integrated properties of the alloy by refining the primary Mg$_2$Si morphology.

The control of texture is challenging in the hot rolling process due to simultaneous recrystallization and deformation. In FCC aluminium alloys, the main concern is to obtain Cube\{100\}\{100\}, deformation texture brass\{110\}\{112\}, copper\{112\}\{111\} and Si\{123\}\{634\} components of proper volume fraction to achieve good formability in the final product\cite{17}. The deformation texture of 6063 Al alloys is strong\{111\} and weak\{100\} dual fiber texture in the center area but is weaker and rotates when approaching the surface\cite{10}. The presence of second phase particles also poses challenges to improving its formability. The size, shape and distribution of second phase particles in the matrix usually play a significant role in deciding the formability of alloys containing two phase particles.

However, few efforts have been devoted to studying the precipitation behaviors of second phases in the $\alpha$-Al matrix of 6063 Al alloys during the solution treatment and artificial aging. Therefore, in this study, the Sr-added 6063 Al alloys were used to compare the grain-refining effects and investigate the existing way of Sr after the solution treatment and artificial aging. Moreover, they were used to study the impact mechanism of Sr element on the second phases in dynamic response recrystallization and analyze the enhancement mechanism of Sr element to 6063 Al alloys. This study will provide significant guidance for the preparation and application of high-performance 6063 Al alloys.

### 2. Experiments

#### 2.1. Preparation of as-cast alloys

The commercially pure Al\{99.7 wt.% Al\}, Mg\{99.8 wt.% Mg\}, Al-5Ti-1B wire\{5 wt.% Ti, 1 wt.% B\}, Al-10Sr\{10 wt.% Sr\} master alloys and Al-22Si\{22 wt.% Si\} master alloys were chosen as starting materials to prepare 6063 Al alloys\{all raw materials are provided by Shanghai and Feng Alloy Material Co., Ltd, China\}. Pure Al\{9 kg\} was melted in a graphite crucible in a vacuum induction furnace. The pure Al and Al-22Si master alloys were put in the graphite crucible and heated to 750 °C for 30 min to observe the complete melting by peephole. The pure Mg, Al-10Sr master alloys and Al-5Ti-1B wire were pressed into the middle of the graphite crucible. All melted raw materials were electromagnetically stirred at 750 °C for 30 min. High-purity argon gas was passed into the titanium tube for refining and degassing of 6 min. Moreover, a layer of slag remover was sprinkled on the surface of the alloy liquid. After heating, the slag was removed. A layer of 40 mm stainless steel filter screen was added to the upper mouth of the mold and then as-cast in a preheated steel mill at 730 °C($\Phi$ 92 × 500 mm).

Alloy samples were taken from different sites of bar-shaped castings and processed into a variety of workpieces for performance testing and analysis. The contents of Mg, Si, Ti and Al were analyzed using the optical emission spectrometer\{OES\}\{OES-6000, Skyray Instrument, China\}, and the content of Sr was analyzed using inductively coupled plasma\{ICP\}\{ICAP-6500DUO, Thermo Electron Corporation, America\}. After cutting and grinding the burr, the ICP sample to be tested was weighed with an electronic balance\{ME104, Mettler, Switzerland\}, and the mass was less than 6 g. Then it was slowly dissolved with 1 mol l$^{-1}$ hydrochloric acid, and the volume is fully dissolved to 500 ml, and then sampling was performed for test, as shown in table 1.

#### 2.2. Extrusion experiment

The as-cast 6063 Al alloys rods ($\phi = 92$ mm) were firstly machined by lathe into a cylindrical sample of $\Phi 90 \times 400$ mm. The alloys were homogenized in a resistance furnace\{490°C, 4 h\} and extruded with an extrusion machine\{Φ90P, Dalian HUAHAN Rubber & Plastic Machinery Co., Ltd, China\} at an extrusion temperature of 520 °C and an extrusion ratio of 40:1. The heating temperature of the abrasive and mould pad was 490°C, and the models were LM4004 and MD90\{Hua Zhu Mould Technology, Co., Ltd, China\}, respectively. A layer of lubricant was applied to the inner surface of the mold to ensure smooth extrusion. The bar after extrusion was a $4 \times 40$ mm rectangular strip and was solid-solution strengthened\{420 °C, 2 h\}. Then, it underwent rapid cooling of water quenching\{T6 condition\}, artificial aging\{175 °C, 2h-195 °C, 2 h\}, and

| Alloy | Si | Mg | Sr | Ti | Al |
|------|----|----|----|----|----|
| 1$^\#$ | 0.40 | 0.58 | 0.00 | 0.01 | Bal |
| 2$^\#$ | 0.42 | 0.59 | 0.26 | 0.01 | Bal |
natural cooling. The cross section which perpendicular to the extrusion direction (ED) for microstructure was observed and analyzed.

2.3. Preparation of metallographic samples
Metallurgy procedure was conducted on the samples according to the standard preparation routines for microstructures characterization. The cast alloys were cut into 10 × 10 × 10 mm by wire cutting, and the section of the microstructures was observed to parallel to the extrusion direction. The sample was first grounded with 400 # sandpaper to remove the surface oxide layer and subsequently grounded with 800 #, 1200 #, 1200 #, 2000 #, 2500 #, 3000 #, 4000 # and 5000 # sandpapers, respectively. The sample was polished with the polishing machine at 400 r min⁻¹ with 0.05 μm of diamond polishing solution. The sample surface was cleaned with distilled water and dried with compressed air; then it was etched with 2% sodium hydroxide solution (2 g of NaOH, 100 ml of distilled water) for 60 s. The microstructure was observed using optical microscopy (OM) (BMM-303E, Shanghai Bimu Yiqi, China).

2.4. Phase and texture test
The phases of alloys were tested by x-ray diffraction (XRD) (X’Pert pro, PANalytical B. V., Holland) under a voltage of 40 kV and a current of 40 mA. The scanning angle ranged from 20° to 90° with a step size of 0.02°. Furthermore, the microstructure was captured by scanning electron microscopy (SEM) (JSM-5610LV/INCA, Oxford Instruments, England) with energy dispersive spectroscopy (EDS) (JSM-5610LV/INCA, Oxford Instruments, England) analysis. Focused ion beam (FIB) (Helios G4 PIFT CXe, ThermoFisher Scientific, America) sample preparation was carried out for transmission electron microscope (TEM) (JEM-F200, JEOL, Japan) analysis, and TEM analysis was conducted on a JEM-F200 microscope with a working voltage of 200 kV. The macrotexture of alloys was tested by electron backscattered diffraction (EBSD) (Oxford-ebsd, Oxford Instruments, England). Firstly, the sample was cut into 4 × 10 mm from as-extruded alloys along the extrusion direction by wire cutting. The tested surface was parallel to the extrusion direction and was grounded using 2000 #, 3000 #, 4000 # and 5000 # sandpapers, respectively. Then the surface was mechanically polished and cleaned with distilled water. The texture test was also carried out under a voltage of 40 kV and a current of 40 mA. Phi and Psi were 0°−360° and 0°−80°, respectively. The (110) and (111) crystal planes were measured.

2.5. Determination of mechanical properties
To study the effect of Sr element on the mechanical properties of 6063 Al alloys, hardness and room temperature tensile tests were performed. First, the sample was extruded, solid-solution strengthened and artificially aged. Then the Brinell hardness was measured by applying 1000 N load for 30 s. Thereinto, five hardness measurements were taken for each sample and were averaged to improve the reliability of results. To determine mechanical properties, samples were first processed into tensile specimens in accordance with GB/T228.1−2010, which were then tested using a universal testing machine at 0.5 mm min⁻¹ (three standard samples for each sample).

3. Results and discussion
3.1. Microstructure analysis of the as-cast 6063 Al alloys
Figure 1 illustrated the OM images of as-cast samples of 6063 Al alloys. As can be seen, each sample represented differences in shapes and distribution of microstructure. Figure 1(a) showed the microstructure of 6063 Al alloys with irregular dendritic and α-Al and the uneven, coarse distribution of the matrix alloys. Thus, dendrite segregation was observed. Moreover, many eutectic compounds were dispersed almost along the grain boundaries, with only a few inside the grains. Figure 1(b) revealed the remarkably refined structure of 6063 Al alloys with Sr addition. The coarse dendrite grain disappeared, and the spacing and dendrite length were significantly reduced, showing cell-like dendrite growth characteristics. Adding Sr to 6063 Al alloys sharply reduced the average size of primary Mg2Si particles, which were refined by forming Al2Si2Sr intermetallic compounds (figure 2). According to the previous report, Sr transformed the crystal morphology of Mg2Si through poisoning, thereby making the crystal grain refined, and the primary Mg2Si particles maintained better morphology [15].

As can be seen from figure 2, the diffraction peaks in all extruded 6063 Al alloys were dominated by the α-Al phase. Figure 2(a) showed the characteristic peaks of alloys (α-Al) and diffraction peaks of some weaker Mg2Si phases. This indicated the relatively low content of the Mg2Si phase in the extruded 6063 Al alloys. Figure 2(b) showed that the characteristic peaks of the Sr-added 6063 Al alloys are α-Al, Mg2Si and Al2Si2Sr. As a result, Mg2Si content decreased and the corresponding peaks were weakened. The Al2Si2Sr peak was very weak, indicating the low content of Sr-added 6063 Al alloys. Al2Si2Sr and Al2Si2Ca were isostructural, both of which
were crystallized in the hexagonal space group P-3m [18], which melted at 1020 °C. The Al₄Sr phase could not be detected maybe due to the generation of heterogeneous compounds of low proportion.

3.2. Effect of Sr on the microstructure of the extruded 6063 Al alloys

Figure 3 showed the SEM image of 6063 Al alloys. As shown in figure 3, the large dark area was α-Al. Mg was solid-dissolved in α-Al with a content of 0.46%, indicating that Mg atoms entered the vacancies of α-Al lattice to form solid solution strengthening. In contrast, the bright spot in the alloy was the Mg₂Si phase. As can be seen in figure 3(a), when Mg₂Si particles were dissolved in the 6063 Al alloys matrix, a small amount of them were dissolved in α-Al.
precipitated in the $\alpha$-Al matrix, making the structure more compact. This indicated that 6063 Al alloys passed through Mg$_2$Si and the formed second phase was dispersion-strengthened, which might affect the mechanical properties of the alloy. Moreover, the Sr element could improve the structure of 6063 Al alloys to varying degrees. After adding Sr to 6063 Al alloys, the large dark area $\alpha$-Al matrix decreased, while the area of bright spots increased, indicating the increasing number of second phases, as shown in figure 3(b). The EDS analysis showed that the main elements of the large bright spots were Al, Si, Mg, and Sr. Combined with XRD analysis, it was identified that the Sr element moved to the grain boundary and aggregated with Al, Si, Mg and other atoms with strong binding force to form compounds of larger size, i.e., Al$_2$Si$_2$Sr and Mg$_2$Si. In figure 3(b), the dark lath-shaped area was the Al$_2$Si$_2$Sr phase, indicating that a small amount of fine Al$_2$Si$_2$Sr particles were precipitated in the $\alpha$-Al matrix, developing a denser structure; the bright oval-shaped point was the Mg$_2$Si phase, clarifying that Mg$_2$Si particles were dissolved in the 6063 Al alloys matrix. This demonstrated that adding Sr element promoted the distortion of the crystal lattice and increased the system energy.

The results showed that after adding Sr element, the grain size was refined, and the numbers of grain boundaries and the second phases increased. Microstructural results suggested that mechanical properties would be increased. This was mainly due to the strong resistance of alloy to dislocation movement. Moreover, fine particles implied that there were a large number of particles per unit volume. Therefore, under identical conditions, the small deformation of a single grain meant the large one that could be withstood before fracture, significantly affecting the plasticity of the alloys. Obviously, the enlarged grain boundary caused by the fine crystal enhanced the resistance of alloys to the dislocation movement, indicating the higher strength of the alloy. Under the action of the added Sr element in 6063 Al alloys, the interface defects were filled, forming a lath-shaped Al$_2$Si$_2$Sr phase and complex compounds (Al$_2$Si$_2$Sr and Mg$_2$Si) with other alloy elements. These compounds were separated at the grain boundary, hindering the continuous growth of a-Al and improving the grain refinement performance.

The rod-shaped phase was determined to be a hexagonal structure by selected area electron diffraction (SAED) (figure 4(b)) and was thus Al$_2$Si$_2$Sr ordered phase. The orientation of the base plane could be judged by the high-resolution (figure 4(c)). In figure 4(c), the crystal plane in the (0001) direction was smaller than that in (0.743 nm), showing that the Al$_2$Si$_2$Sr phase was strongly affected by solution atoms. The results showed that solution strengthening and secondary phase strengthening at grain boundary changed the properties of the alloy. The SAED of the short rod phase was shown in figure 4(f). The hexagonal structure of the short rod-shaped phase was determined by the crystal plane distance and reciprocal space distance, indicating that the phase was...
also an Al$_2$Si$_2$Sr ordered phase. Al$_2$Si$_2$Sr was formed at the Si/liquid interface, which changed the growth mode of Si and the microstructure of the alloys [19]. According to the diffraction spot and fast Fourier transform (FFT), the crystal plane is clear (figure 4(e)). The spacing of the short rod-shaped crystal plane was 0.7821 nm, larger than that of the rod-shaped crystal plane, indicating the lattice distortion. Figure 4(f) was an inverse fast Fourier transform (IFFT) image of a relatively recent spot. Large distortions (marked by a red circle) could still be seen on some faces, with a small number of dislocations (indicated by T). The dispersion of the Al$_2$Si$_2$Sr phase could be used to pin dislocations and increase the required shear stress; also, recrystallization nucleation and growth were inhibited. Finally, the extrusion properties of 6063 Al alloys were changed.

Figure 5 showed the IPF diagram, grain boundary diagram and orientation difference angle of extruded 6063 Al alloys. As shown in figures 5(a) and (b), the distribution diagram of grain orientation was obvious, and the grain boundary was clear. The grain orientation had a certain anisotropy. The corresponding size and angle grain boundary distribution are shown in figures 5(b) and (e). The green lines indicated low-angle grain boundaries (LABs) with a misorientation angle ranging from 2° to 15°, while the black lines represented high-angle grain boundaries (HABs) with a misorientation angle over 15°. It could be seen that the majority of the two types of alloys consisted of coarse equiaxed grains, and the average grain size was around 33.45 and 24.04 μm, respectively. The fraction of LABs was defined as f and the misorientation angles smaller than 2° were excluded. Figures 5(c) and (f) showed that the misorientation angle was mainly concentrated in the relatively less LABs. The appearance of many boundaries indicated that the density of internal defects in the material gradually increased, identifying the existence of deformed structure and strong texture. The IPF diagram (figure 5(d)) showed that with the addition of 0.26% Sr in 6063 Al alloys, the content of colored grains doubled, the grains became smaller, and the small-angle grain boundaries increased. It was observed that the 〈001〉 crystal orientation in the alloy was strengthened, while the 〈101〉 crystal orientation was weakened because the preferential adsorption of Sr on the surface inhibited the growth rate of Sr to the 〈100〉 crystal orientation.

As a general rule, the nugget zone often possesses a more homogeneous structure and a better mechanical performance than other zones [20]. After adding Sr to the 6063 Al alloys, the broken and elongated deformed grains become uniform and fine equiaxed grains, indicating that the formation of a new Al$_2$Si$_2$Sr phase (figure 2) affected the microstructure of the alloy. The Al$_2$Si$_2$Sr phase aluminum alloy provides a heterogeneous nucleation core during dynamic re-crystallization, producing a small distortionless during dynamic re-crystallization. The new crystal grains have a smaller overall size, thus increasing the grain boundary area per unit volume, the resistance to the movement of dislocation, and the strength of the alloy. The generation of numerous new grains significantly decreases the proportion of large-angle grain boundaries but increases that of small-angle grain boundaries, further raising dislocation density and the alloy strength. Due to the dislocation-particle interaction, Al$_2$Si$_2$Sr particles promote the generation of dislocations in Sr-added 6063 Al alloys, and the pinning effect of Al$_2$Si$_2$Sr particles effectively hinders the movement of dislocations, thereby affecting the mobility of dislocations. This finding is consistent with the results by Zhao et al [21].
Figure 5 shows statistical graphs of the recrystallization, substructure and deformed grains of 6063 Al alloys. After adding Sr to 6063 Al alloys, the recrystallized grains decreased, while the substructure and deformed grains increased. The recrystallized grains were reduced from 90.45% (figures 6(a) and (b)) to 75.45% (figures 6(c) and (d)). The substructure grains and deformed grains increased from 3.33% and 0.56% to 21.09% and 3.43%, respectively. The dynamic recovery and recrystallization were closely related to the mobility of grain boundaries and dislocations, which could be significantly different between the two samples. Microstructural results showed that adding Sr would alter the mechanical properties of 6063 Al alloys.

As shown in figure 6(a), fewer substructures were found, verifying that the dislocation network on the adjacent sub-grain boundaries dissociated, broke up, and was transferred to other sub-crystals during dynamic recovery and recrystallization, resulting in the disappearance of the sub-grain boundaries and the formation of sub-grain boundaries. Additionally, due to the continuous movement of dislocations to the new sub-grain boundary, the small-angle grain boundary was gradually transformed into a large-angle one with a faster migration speed and thus serving as a recrystallized crystal nucleus. Moreover, the increase of recrystallized grains and smaller substructure grains changed the mechanical properties of the alloy. In figure 6(c), the recrystallization grains were reduced, proving that the increased recrystallization energy after adding Sr blocked the grain boundaries and hindered the recrystallization and abnormal grain growth. The increasing substructure and deformed grains indicated that during the dynamic recovery and recrystallization, due to the presence of Sr element, the cross slip of screw dislocations and the climbing of edge dislocations in the recovery stage of dislocations resulted in polygons, regularization of dislocation, and entangled dislocation cell walls. In addition, the high stacking fault energy led to the formation of a stable subcrystalline structure. After dynamic recovery, dynamic recrystallization was inhibited. As a result, the substructure and deformed grains increased; the size and proportion of the recrystallization grain decreased, indicating the significant effect of Sr on the dynamic recovery and recrystallization. Substructure and deformed grains increase, and the internal dislocation density of the alloy was higher.

Adding Sr element enhanced the distortion of the crystal lattice and the energy of the system. In order to keep the free energy of the system at the lowest level, Sr elements were moved to the grain boundaries to form Al2Si2Sr intermetallic compounds with Al and Si atoms, decreasing the relative content of the Mg2Si phase. The growth of Mg2Si crystal grains was restricted, and fine Mg2Si and Al2Si2Sr were formed. During the solidification, Sr was enriched at the front of the solid-liquid interface and the branch junction. Sr was combined with other elements to form an Al2Si2Sr phase with a high melting point to fill the interface defects. These compounds were segregated at the grain boundaries and hindered the continuous growth of aluminum.
3.3. Texture analysis of extruded 6063Al alloys

Figure 7 showed the EBSD pole diagram of extruded 6063 Al alloys. Compared with the standard \((110)\) pole figure \([22]\), the texture of 6063 Al alloys mainly concentrated in \((110)\) and \((101)\), along with a small amount of \((102)\) and \((021)\) orientation (figure 7(a)); after adding Sr, it mainly concentrated in \((110)\) and \((101)\) (figure 7(b)).

Figure 8 showed the ODF diagram of 6063 Al alloys. As can be seen, the main texture of 6063 Al alloys was Cube \(\{100\}\ \{001\}\), Goss \(\{110\}\ \{001\}\), trace S \(\{123\}\ \{634\}\) texture, \(\{111\}\ \{112\}\) texture, \(\{025\}\ \{100\}\) texture and \(\{111\}\ \{110\}\) texture. After adding Sr to 6063 Al alloys (figure 9), the cube texture was enhanced, while \(\{111\}\ \{112\}\) texture, \(\{025\}\ \{100\}\) texture and \(\{111\}\ \{110\}\) texture were weakened. The GOSS texture and S texture disappeared. However, it should be pointed out that the EBSD scanning area was limited, which might cause an unusual concentration of texture.

The main texture of 6063 Al alloys was the cube, Goss, brass, and S texture. Cube texture was considered to be a metastable component and grew during recrystallization. Sr is added to 6063 Al alloys during dynamic recovery and recrystallization. A large number of substructures (figure 6 (c) and (d)) led to an increase in the cube texture and the disappearance of Goss texture and S texture. It is reported that the cube texture has low storage energy and is easy to generate cube-oriented grains by deformed cubic bands, and the deformed grains serve as the subsequent recrystallization nuclei. Its origin is similar to the orientation of the deformed grains that produce it. Also, Sr and Mg\textsubscript{2}Si affect dislocation movement or slip type and further control the recrystallization texture by promoting cube grains and inhibiting Goss grains.
3.4. Mechanical property analysis of the extruded 6063Al alloys

The mechanical properties of 6063Al alloys are shown in figure 10. It can be seen that the tensile strength of 6063 Al alloys was improved from 203.53 MPa to 324.98 MPa, the yield strength increased from 157.12 MPa to 266.11 MPa. The Brinell hardness rose from 60.67 to 82.29 HB, and elongation increased from 11.13% to 12.57% (figure 9). This result indicated that adding Sr to the master alloys improved the elongation of 6063 Al alloys. By comparing the structure, the alloy grains became smaller after adding Sr to the 6063 Al alloys, indicating that Sr refined the Mg2Si phase and strengthened the mechanical properties of the 6063 Al alloys through grain refinement strengthening. Moreover, due to the addition of Sr to 6063 Al alloys, Al2Si2Sr intermetallic compounds were formed in the alloy. The pinning effect of Al2Si2Sr particles effectively hindered the movement of dislocations, thereby enhancing the mechanical properties of 6063 Al alloys.

4. Conclusions

This paper investigated the strengthening mechanism of the Sr element on 6063 Al alloys. The conclusions are obtained as follows.

(1) The phase structure of the as-cast 6063 Al alloys changes after adding Sr. The as-cast 6063Al alloys are mainly composed of α-Al matrix and Mg2Si phase, and the grains are not refined. After adding Sr, Al2Sr2Si particles appear in the α-Al matrix of as-cast 6063 aluminum alloy, and the grains are significantly refined.

(2) Adding Sr to 6063 Al alloys converts the microstructure of the alloys. Specifically, the LABs increase while the HABs decrease. A large number of substructures form into dynamic recovery recrystallization.
(3) The texture of 6063 Al alloys is mainly concentrated in two directions, i.e., (110) and (101); the directions (102) and (201) are relatively weak. The main textures are Cube [1 00] // (001) and Goss [1 10] // (001). The texture of 6063 Al alloys with Sr addition is mainly concentrated in the (110) and (101) directions, and the main texture is Cube [1 00] // (001).

(4) The 6063 Al alloys with Sr addition have good mechanical properties and elongation, indicating the main role of grain refinement, solid solution strengthening and dispersion strengthening.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Data access statement

Any data that support the findings of this study are included within the article.

Conflict of interest statement

The authors have declared that no competing interests exist.

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