Effects of Helmholtz coil magnetic fields on microstructure and mechanical properties for sand-cast A201 Al-Cu alloy

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Abstract

In this report, the effects of magnetic fields by using Helmholtz coils on the microstructures and mechanical properties of sand-casting Al-Cu alloys were firstly investigated. Due to the magnetic field stirring effect during the solidification process, the average grain size of sand-casting A201 ingots decreased, and the uniformity of α-Al grain increased. The grain refinement by the magnetic fields equipped with Helmholtz coils enhanced the mechanical properties of sand-casting A201 ingots, including hardness, yield strength, ultimate tensile strength and elongation. Meanwhile, according to the characterization of x-ray diffraction, preferred orientation (111) planes of α-Al phase was observed as the increase of the magnetic field. The magnetic field of Helmholtz coils provided the Lorenz force to agitate the melt during the solidification of sand-casting Al-Cu ingots, which had influence on the migration of solid-liquid interface and the rotation of the single-crystal nucleus. In summary, an easy and low-cost technique was proposed to improve the mechanical properties of sand-casting A201 alloys.

1. Introduction

Aluminum alloy is one of light metals with high strength for engineering materials, applied in the aerospace, military and automotive industries. Aluminum alloys are classified into two categories: wrought alloy and casting alloy. The wrought aluminum alloy, identified as the four-digit numerical designations, is normally produced in ingot form and then worked by scalping, homogenizing and rolling process. Cast aluminum alloy is usually used in a final or near-final shape of ingots after the casting process. Cast aluminum alloy is designated by three-digit number or four-digit number with a decimal between third- and fourth-digit [1]. Aluminum alloys have relatively low melting temperatures, which is suitable for casting technique. Among aluminum alloys, copper is one of the most important alloying elements for aluminum. The casting Al-Cu alloy is named as 2xx. Copper can provide substantial increases in strength for aluminum alloys due to the solid solution and precipitate formation [2, 3]. Besides, the mechanical properties of aluminum alloys are essentially related to their grain microstructure. The casting conditions and parameters can affect the ultimate tensile strength of the Al-1.5% Cu alloy [4]. The strength of the Al-Cu decreases in the lower cooling rate and at higher melt overheating. Therefore, the grain refinement of casting Al-Cu alloy is one of the solution to enhance their mechanical properties including yield strength and ductility, and it can also prevent the hot tearing during the solidification process [5]. Grain refinement effect of Al-Cu ingots was also proposed to improve the reliability during the manufacturing procedures.

To improve the mechanical properties of aluminum alloys through microstructure refinement, Vives C. et al firstly proposed a method of applying electromagnetic vibration to the solidification process of metals in 1993 [6]. Then, the continuous casting process with the electromagnetic field was employed in several alloys. For instance, low-frequency magnetic field was applied to continuous casting 7075 aluminum alloys. The electromagnetic casting process was able to decrease the macrosegregation phenomenon [7]. At the frequency 30 Hz of electromagnetic coils, the macrosegregation on 7075 aluminum alloy was completely disappeared. Grain
refinement of the Al-Zn-Mg-Cu alloy was also demonstrated by low-frequency electromagnetic direct chill (DC) casting process [8]. The DC casting process of aluminum alloys was added the coils with current to generate the magnetic field. It can refine the grain size of casting ingots to improve mechanical properties of 2024 Al-Cu and 2A97 Al-Li alloys [9, 10]. During the solidification of alloys, the migration of grain boundary and phase interface can be affected by a magnetic field. Therefore, the grain size, boundary and orientation distribution can be modified by a magnetic field [11, 12]. Moreover, to refine the microstructure of ingots during the solidification process, the pulsed magnetic field and electric current pulse with parallel electrodes were proposed for austenitic stainless steel and pure aluminum, respectively [13, 14]. A low-voltage pulsed magnetic field had impact on the microstructure of the Mg-Al-Zn alloy [15]. The yield strength was improved due to the refinement of the grain, while the ultimate tensile strength slightly decreased. This technique was also applied in the as-cast superalloy IN718 [16] and ceramic-reinforced aluminum matrix composites [17]. A combination of static magnetic field and pulsed magnetic field made more refining microstructure on 7075 aluminum alloy [18]. Besides the grain refinement by applying a magnetic field, electromagnetic field can be used for the removal of inclusions from the liquid aluminum alloys by alternating-current magnetic fields such as rotating magnetic field (RMF), travelling magnetic field (TMF) or combined both types [19, 20]. The combined magnetic field was effective for the metal purification procedure. The combination of RMF and TMF can remove the silicon particles from the molten alloy [21].

So far, various electromagnetic techniques were employed to increase the mechanical properties of casting ingots, especially for continuous casting process of aluminum alloys. However, among the various casting techniques, sand-casting aluminum alloy normally has lower tensile strengths than permanent-mold-casting or die-casting aluminum alloys because of their relatively large dendritic cell size after the longer-term solidification process [5]. Besides, the sand-casting workpieces are normally in a larger size and various shapes. The study about the sand-casting technique with magnetic field is rare.

Helmholtz coils are a pair of identical coils which separate by distance to their radius. The coils are used to develop a small volume of the uniform magnetic field in the space between the coils [22]. The Helmholtz coils can be constructed easily, and their magnetic field can be calculated easily. Magnetic field by Helmholtz coils is useful for testing equipment that needs a low-frequency magnetic field. The uniformity of the magnetic field at the center of the Helmholtz coils has been examined and investigated [23, 24]. The optimization of the parameters on the coils pairs was needed to maintain the required field uniformity for the applications [25, 26]. Based on the magnetic field by Helmholtz coils, helical and Bouligand porous Fe3O4 scaffolds were fabricated by the dynamic low strength magnetic field free casting to improve the mechanical properties [27]. Until now, the report about the manufacturing process equipped with Helmholtz coils is still not popular.

In this report, we firstly proposed an easy technique to provide the magnetic field by Helmholtz coils for sand-casting A201 Al-Cu alloys. Because of the lower solidification rate of sand-casting process, the dendrite and large grain of casting ingots had disadvantage on the mechanical properties of Al-Cu alloys. A magnetic field applied easily by Helmholtz coils could have more influence on their mechanical properties during the long-term solidification procedure. After the sand-casting process, the microstructure and mechanical properties of A201 alloys were investigated. The mechanism of grain preferred orientation during the solidification with magnetic field was also studied.

2. Materials and methods

The chemical composition of A201 aluminum alloy (Al-Cu alloy) is listed in table 1. The solidification mould was prepared by crystal quartz sand and sodium silicate. The raw material of A201 alloy was melted at 790 °C by using the electrical resistance furnace. Before the casting process, the molten metal was refined with argon gas for 5 min using a rotary graphite degasser, and the slag was removed. Then, the sand-casting process was conducted at a fixed pouring temperature 710 °C of the molten metal. The magnetic field was supplied by the Helmholtz coils with an autotransformer. The experimental layout is shown in figure 1. During the casting process, the magnetic field was applied by AC current (60 Hz) on the Helmholtz coils. The dimension of Helmholtz coils in coil number of 1000 is shown in figure 2. The magnetic field was applied until the ingots completely solidified.
Two specimens were prepared in one casting process. The output voltages of autotransformer were set at 0, 100, 200 and 300 volts, which corresponded to the magnetic fields measured by a Gauss meter as 0, 1.45, 3.01 and 5.55 mini-Tesla (mT), respectively.

After the sand-casting process, samples were inspected by optical microscopy, Rockwell hardness tester, tensile testing machine and x-ray diffraction to obtain the microstructure and mechanical properties of A201 alloys. The tensile strength of the material was measured by using SHIMADZU AG-1 100 KN tensile testing machine in the strain rate of 1 mm/min. The shape and dimensions of tensile specimens are shown in figure 3. Mitutoyo Ar-10 was employed for the Rockwell hardness test. Eight testing points were conducted on the testing strip of ingots. Then the average hardness value was obtained from six testing points by removing the maximum and minimum values. For the metallographic observation, the optical microscopy (OM) is the model of OLYMPUS BX41M. The samples were etched by 0.5% hydrofluoric acid solution after polished. It was used to observe the microstructure of Al-Cu alloys and to obtain their average grain-size of A201 ingots after sand-casting process without or with different magnetic fields. The average grain-size was calculated by using interception methods.

Moreover, x-ray diffraction on the casting ingots was conducted by using Rigaku D/max-2500 x-ray equipped with the target of Cu ($\lambda$: 1.5418 Å). The operating parameters included the voltage 30 kV, current 50 mA, scanning range from 20° to 80° and the scanning rate of 1.5 degrees min⁻¹.
3. Results and discussion

3.1. Microstructure analysis

During the sand-casting process of A201 alloys, the alternating magnetic field in the strength of 0, 1.45, 3.01 and 5.55 mT was applied for the solidification. The magnetic field was maintained until the casting ingots completely solidified. The microstructure of A201 ingots in the center part of four samples are shown in figure 4. The \(\alpha\)-Al primary phase with polycrystalline grains was presented. Meanwhile, the average grain size can be calculated by the OM images. The average grain size was refined from 78.5 \(\mu\)m (figure 4(A), without an external magnetic field) to 68.6 \(\mu\)m (figure 4(D), with the magnetic field as 5.55 mT). When the strength of the magnetic field increased, the average grain size of casting ingots decreased. The phenomenon of grain refinement for A201 alloys was observed by increasing the magnetic field. This is because the Lorentz force was generated by the magnetic field to stir back and forth during the solidification process of A201 alloys. The dendrite fragmentation and intrinsic grain refinement by the magnetic field for Al-15Cu alloy have also been investigated by in situ synchrotron x-ray radiography [28].

Due to the different solidification rate for inner and outer part of sand-casting ingots, a comparison of the microstructure between the center and edge parts of specimens are shown in figure 5. For the sample without magnetic field in figures 5(A) and (C), it can be found that the A201 ingot had a longer grain-growth time for the inner part of specimen during the solidification process. The grain coarsening significantly occurred as shown in figure 5(C). The smaller grain size at the edge of specimen, shown in figure 5(A), came from the higher undercooling by the lower temperature of sand mould. This is a typical microstructure of solidification process [2]. On the contrary, the microstructures at the edge and center parts of the casting ingot with magnetic field of 5.55 mT are performed in figures 5(B) and (D), and the grain refinement can be observed obviously. During the solidification process, the center part of the ingot had longer-term solidification than the inner part of the ingot. Therefore, the applied magnetic field had more influence on the molten aluminum alloys for the center part of.
the ingot. After more stirring effect by the magnetic field, smaller grain size of the casting ingot was observed in figure 5(D). Those different microstructures of specimens can influence their mechanical properties such as hardness, strength and ductility, which will be discussed in the following section.

3.2. Rockwell hardness analysis

The Rockwell hardness of A201 ingots for different magnetic fields is shown in figure 6. The data shows that their average hardness increased as the applied magnetic field increased. The highest average hardness 43.6 HRB of A201 ingots was obtained in the magnetic field strength of 5.55 mT. The deviation of the hardness value also decreased with the increasing strength of the magnetic field. The stirring effect by the applied magnetic field did effectively improve the overall uniformity of the casting ingot to lower deviation value of Rockwell hardness. As the result of microstructure observation, grain refinement of A201 ingots by the magnetic field improved their hardness. The better uniformity of microstructure decreased the deviation of the hardness in an ingot as well, which could enhance the reliability of sand-casting process for A201 alloys.

3.3. Tensile test

To further analyse the mechanical properties of the sand-casting A201 ingots, tensile test was conducted to have yield strength (YS), ultimate tensile strength (UTS) and elongation. The ultimate tensile strength and yield
The tensile strength of A201 casting ingots are shown in Figure 7. When the magnetic field strength increased, the tensile strength also increased slightly and reached the maximum as the magnetic field strength at 5.55 mT. The magnetic field by Helmholtz coils for the sand-casting of A201 alloys precisely enhanced the mechanical properties. This is because of the grain refinement effect. As the Hall-Petch relation, the performance of yield stress is related to the grain size of the materials [29].

Meanwhile, the ductility of A201 ingots is performed by the elongation after the tensile test. Their elongation values are shown in Figure 8. The elongation of A201 ingots increased as the magnetic field increased during the solidification. Normally, the small and uniform grain structure in the materials can perform the better ductility [30]. The better ductility of sand-casting ingots could have advantage for the following polishing and machining processes of A201 workpieces.

### 3.4. X-ray diffraction analysis

XRD was used to identify the crystal phase and grain orientation of as-cast A201 ingots. The result of XRD measurement on the surface of A201 ingots is shown in Figure 9. The typical planes of α phase for A201 alloys included (111), (200), (220) and (311). Interestingly, the preferred orientation of as-cast ingots gradually changed from (200) to (111) when the strength of the magnetic field increased. As the magnetic field reached 5.55 mT, the crystallographic texture almost completely turned to (111) plane.

Solidification of a casting ingot depends on the mechanism of nucleation and grain growth. The grain growth of polycrystalline materials comes from the control of grain boundary migration. Besides the grain refinement by the applied magnetic fields, the grain boundary character distribution in non-ferromagnetic anisotropic materials can be also influenced by the magnetic fields. The motion of grain boundary can be modified by the gradient of the magnetic free energy density. Therefore, the application of an external magnetic field during the solidification could result in a growth of new preferentially oriented grains [11].
The single-crystal nucleuses or clusters in the molten metal have magnetocrystalline anisotropy, and the magnetic susceptibility for aluminum reaches the maximum in the crystal plane of $[310]$ $[31, 32]$. The magnetic alignment of Al-Cu nucleuses at the interface of the solid and liquid phases can be schematically shown in figure 10. In the variable magnetic field, the oscillations influence the process of crystallization, especially in liquid phase. A nucleus crystallizing from the melt can be oriented by the magnetic field $[33]$. When a crystal with anisotropic magnetic property is placed in a magnetic field, the magnetic field can significantly affect the minimum energy of the crystal thermodynamically. The free energy difference of the crystal axis must be greater than the thermal energy. The crystal is subjected to a magnetic field and the crystal axis generates its magnetic free energy. To reduce the magnetization energy, the easy magnetization crystal plane axis will be rotated to the parallel direction to achieve a stable orientation for the solidification process. Therefore, the applied magnetic field can make the preferred crystalline orientation of A201 sand-casting ingots.

Figure 9. XRD measurements of as-cast A201 alloys with different magnetic fields.

Figure 10. Schematic diagram of the Al-Cu nucleuses under the magnetic fields during the solidification.
4. Conclusion

In this work, the magnetic field applied by the Helmholtz coils was firstly integrated to the sand-casting process of A201 alloys. The grain refinement of A201 ingots was observed by increasing the external magnetic field. As the strength of the magnetic field increased, the average grain size of casting ingots decreased. The grain refinement effect by the Helmholtz coils also enhanced the mechanical properties of as-cast ingots mechanical properties, including the hardness, yield strength, ultimate tensile strength, and elongation. At the maximum magnetic field (5.55 mT), the average Rockwell hardness reached 43.6 HRBs with the smallest hardness deviation among all samples. The highest yield strength and elongation value were obtained in the tensile test. This grain refinement of A201 alloys by magnetic field could also improve the product reliability of sand-casting A201 workpieces. Finally, XRD results showed primarily α phase of Al-Cu alloys and had preferred orientation (111) by the application of an alternating magnetic field as 5.55 mT. The magnetic field by Helmholtz coils could have the influence on motion of grain boundary and rotation the single-crystal nucleuses during the solidification process of A201 ingots.

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