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EFFECTS OF UNIFORM DIRECT CHILL CASTING PROCESS ON STRUCTURE OF 7055 ALLOY BILLET

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ABSTRACT

To obtain large-sized billets with fine grains and homogeneous elements distribution, uniform direct chill (UDC) casting process, based on annular electromagnetic stirring coupling with intercooling, was employed to produce 7055 alloy billets with a size of Φ584 mm in this study. The results indicated that there were the coupled effects of annular electromagnetic stirring and intercooling on grain refinement and element homogenization, and also the billets produced by the UDC casting process showed excellent hot workability in comparison to the normal direct chill casting process.

KEYWORDS

7055 alloy, Aluminium alloy, Direct chill casting, electromagnetic stirring, Intercooling

INTRODUCTION

The high solute 7055 aluminium alloy has a wonderful combination of high specific strength and hardness, good resistance to stress corrosion cracking and high fracture toughness, which is very useful in aerospace application (Yan et al., 2013; Mondal & Mukhopadhyay, 2005). The production of large-sized 7055 alloy billets with high quality is the basic condition for the subsequent application of 7055 alloy to the aircraft. Inhomogeneous microstructures and performances of 7055 billets result from the high alloying element content and the inhomogeneous cooling condition in different regions of billets during the conventional direct chill casting (Paramatmuni et al., 2004; Lalpoor et al., 2011), which will bring bad influence to processing property, functional performance and utilization rate of materials. To alleviate segregation and obtain fine and uniform grains, some effective treatment methods were proposed including electromagnetic stirring (EMS) (Vives, 1989), ultrasonic vibrating (Zhang et al., 2011) and melt conditioning (Fan et al., 2013), on the melt to obtain fine and uniform grains. However, these methods could not effectively decrease the large temperature difference between central and periphery parts of the billet, because the solidification mainly depends on outside cooling including mould cooling and water spraying cooling. To change the heat extraction pattern of the billet functioned solely from the outer surface, based on annular electromagnetic stirring (A-EMS) invented by Xu et al. (2010), Luo et al. (2017) proposed uniform direct chill (UDC) casting coupling A-EMS with intercooling in the direct chill (DC) casting process. An in-mold cooler was inserted to the melt sump, and thus the alloy melt temperature and concentration at solidification front become more uniform.

In this study, the effects of UDC casting process on grain refinement and segregation of 7055 alloy billets were investigated, and the heat deformation property of the 7055 alloy billets after homogenization in cases with and without UDC casting process were evaluated.

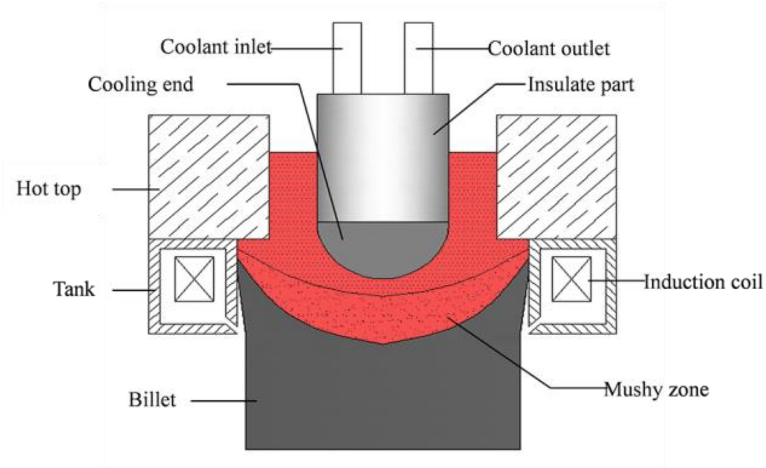

Figure 1. Schematic view of the uniform direct chill (UDC) casting process

EXPERIMENT

The schematic view of industry-scale UDC caster with billet diameter of 584 mm is shown in Figure 1. Compared with normal DC (NDC) casting, an in-mold cooler with a cooling end made of highly pure graphite was inserted in the melt as well as an electromagnetic stirrer with the arrangement of six water-cooled copper coils fed with a three-phase electric current was installed outside of the mold.

The commercial 7055 alloy (Al–7.8Zn–2.0Mg–2.3Cu–0.18Zr–0.081Fe–0.024Si, wt.%) was melted in an induction furnace. The melt was transferred into a holding furnace for degassing and filtering. The melt was poured into the hot top with a temperature of 200°C. When the casting process proceeded at a stable stage, the electromagnetic stirring system was started, and the in-mould cooler with initial temperature of 200ºC was inserted in the sump along the central vertical axis of the mould in the caster. The NDC and UDC casting process parameters were shown in Table 1.

The as-cast grain structures of transverse cross-sections were observed using conventional metallographic techniques. The samples taken from the transverse cross-section of the billet were electro-polished in 3% HBF_4. For as-cast structural studies, a polarized light optical microscope equipped with an image analysis system (Carl Zeiss Axiovert 200 MAT) was used. The chemical composition of the cross-section of the billets was evaluated by means of FOUNDRY-MASTER Pro. Axisymmetric compression samples of φ10 mm × 15 mm were machined from 0.5 radius position of the billets after homogenized at 470°C for 24 h. The flat ends of the samples were recessed to groove with a depth of 0.2 mm. The hot compression tests were performed on a computer servo-controlled Gleeble−1500D system with temperature range of 300–450°C and strain rate range from 0.01 to 10 s^{-1}. The samples were effectively lubricated with graphite and deformed to a true strain of 0.7. Using the flow stress data, power dissipation efficiency and flow instability were evaluated for different strain rates and temperatures. The processing maps were developed for 0.5 strain for the alloy.

Table 1. Casting process parameters of NDC and UDC

Parameters	NDC	UDC
Pouring temperature(K)	1003–1033	1003–1033
Casting speed ($mm\bullet min^{-1}$)	25–30	25–30
Cooling water ($m^3\bullet h^{-1}$)	8–10	8–10
Electromagnetic current (A)	-	90
Electromagnetic frequency (Hz)	-	3
Cooler diameter(mm)	-	200
Cooling rate ($W\bullet m^{-2}\bullet K^{-1}$)	-	500–1000

RESULTS

To assess the effect of the UDC casting on grain refinement of 7055 alloy, the as-cast microstructures of 7055 alloy billets obtained by NDC casting and UDC casting were compared as shown in Figure 2. Without melt treatment, the structure of the billet obtained by NDC casting is typical large dendrites in the edge, the 1/2 radius and the centre, and the grain size is at millimetre grade throughout the billet. After applied by intercooling and A-EMS, the grains are remarkably refined to less than 300 μm, the finer grain size is achieved homogeneously throughout the billet.

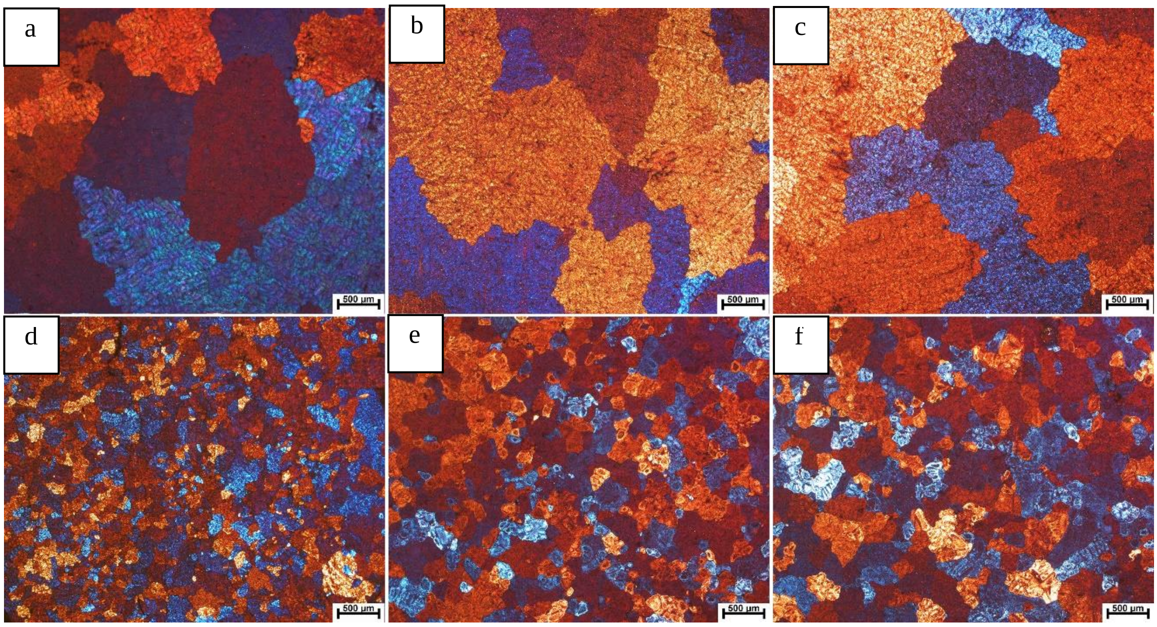

Figure 2. Micrographs of radial cross sections of the edge (a, d), the 1/2 radius (b, e) and the centre (c, f) of the 7055 billets prepared using NDC casting (a, b and c) and UDC casting (d, e and f).

To investigate the segregation of the billet, relative segregation, *S*, was proposed to characterize the segregation level. The relative segregation is defined as:

$$S = \frac{(C_i - C_0)}{C_0} \times 100\% \quad (1)$$

Where, C_i is the content of a certain element in the *i* position of the billet, C_0 is the average value of the element of the billet. C_i is more than 0, indicating positive segregation, C_i is less than 0, indicating negative segregation. Figure 3 shows relative segregation of Zn, Mg and Cu along radical direction of billets prepared by NDC and UDC casting. There were negative surface segregation, positive 1/2 radius segregation and negative centreline segregation in billet obtained by NDC casting, which is quite typical segregation of large-sized DC casting with high alloy contents. However, the segregations in surface, 1/2 radius and centreline of billet obtained by UDC casting were alleviated greatly.

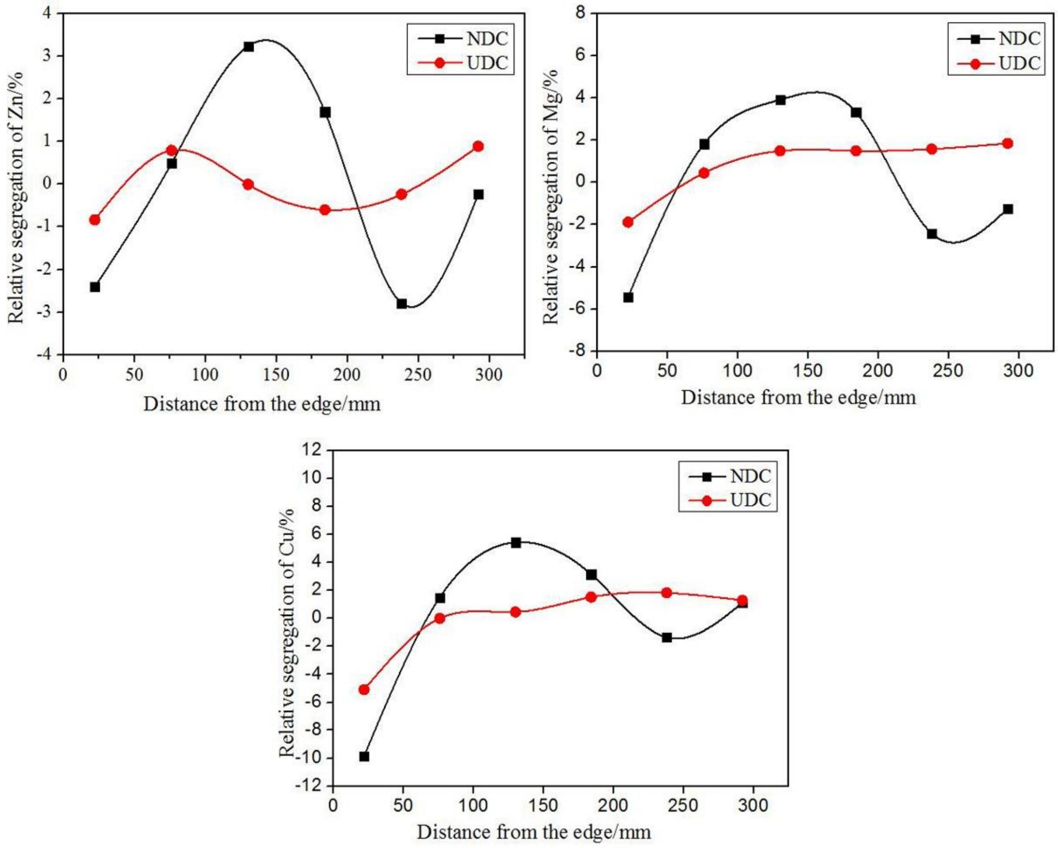

Figure 3. Relative segregation of Zn, Mg and Cu along radical direction of billets prepared by NDC and UDC casting

Processing maps were developed for 0.5 strain by superimposing the instability map on the power dissipation map was shown in Figure 4, in which the shaded domain represents the unstable region and the rest domain represents the safe processing region. The efficiency of power dissipation η indicates the power dissipation by microstructure evolution. The material deformed in the condition with higher efficiency of power dissipation usually shows higher workability (Yang et al., 2013). The processing maps at a strain of 0.5 for 7055 alloy prepared by NDC casting and UDC casting are respectively shown in Figure 4a and Figure 4b. The typical safe domain for billet prepared by the NDC casting occur at high temperature (360–450°C) and low strain rates (0.01–0.1 s^{-1}). However, for the billet prepared by UDC casting, the safe domain has higher efficiency of power dissipation and occurred at wider temperature range (300–450°C) and strain rates (0.01–0.1 s^{-1}). The above results indicate that the instable area at low temperature and low strain rate is transferred to safe area by UDC casting. The processing temperature range is enlarged that provides much more opportunity for workability. Comparing the two process maps, it is obvious that the contour line of the efficiency of power dissipation in the safe domain is more uniform and increases more slowly and more stable as the temperature increases, which exhibits that UDC casting is beneficial for the control of hot deformation and microstructure of the prediction.

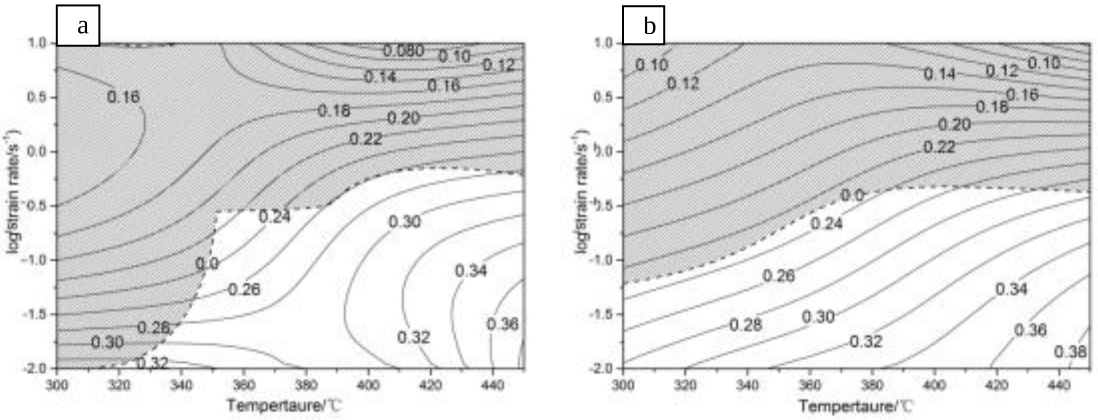

Figure 4. Processing map at a strain of 0.5 for the 7055 alloy billets prepared by NDC (a) and UDC casting (b)

DISCUSSION

The effects of A-EMS and intercooling on the mechanical properties including hot workability of the billets are directly related to the structure and segregation. The grain size during solidification is mainly dependent on the heterogeneous nucleation of the solid phase and the subsequent growth of the newly formed nuclei where a sufficient amount of nuclei is of great importance for grain refinement (Haghayeghi & Kapranos, 2013). The application of A-EMS and intercooling in DC casting of billets contribute to the nucleation process in different ways. On the one hand, insertion of in-mold cooler into the melt sump can remove heat from the sump center, in this way, the melt is chilled from the outer and inner surfaces simultaneously (Luo et al., 2017). As a result, the cooling rate was improved, and it favors the survival of nuclei and the formation of fine grains, and the temperature gradient from the edge to center in the sump is decreased that could make the sump shallow, which is beneficial for alloying elements distributing uniformly. On the other hand, when A-EMS was applied, a strong Lorentz force is generated resulting in forced convection in the annular gap and the sump (Bai et al., 2009). Initially solidified grains forming on the mold and the in-mold cooler are detached and carried away to the bulk of the melt by the induced liquid flow, supplying large quantities of nucleation sites. The growing nuclei and grains are then transferred by the forced convection throughout the melt, allowing nucleation to take place across the melt. As the nuclei and grains transferred throughout the melt by the forced convection, the alloying elements including Zn, Mg and Cu were also homogeneously transferred in the whole melt.

By coupling A-EMS and intercooling, the UDC casting can provide a uniform temperature gradient, uniform composition distribution and shallow sump, so the problems such as coarse, inhomogeneous structures at different parts of the billets and serious segregation can be eliminated fully. So, it is well known that the 7055 billets with fine and uniform structure benefits for a wide hot workability window.

CONCLUSIONS

The coupling effects of A-EMS and intercooling on the solidification of 7055 alloy billet could remarkably refine microstructure and homogenize the distribution of alloying elements. The grain size are less than 300 μm and obviously finer than about millimeters of billets by using NDC casting. And also the negative surface segregation, positive 1/2 radius segregation and negative centreline segregation were decreased greatly. The typical safe domain for billet prepared by the NDC casting occur at high temperature (360–450°C) and low strain rates (0.01–0.1 s^{-1}). However, for the billets prepared by UDC casting, the safe domain has higher efficiency of power dissipation and wider temperature range (300–450°C) and strain rates (0.01–0.1 s^{-1}). The UDC casting billets are beneficial for enlarging processing temperature range and providing much more opportunity for workability.

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