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As-cast structure and tensile properties of AZ80 magnesium alloy DC cast with low-voltage pulsed magnetic field

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Abstract: The effects of a low-voltage pulsed magnetic field on the solidified structure and mechanical properties of DC casting AZ80 magnesium alloy were investigated. The results showed that the solidified structure of the DC casting AZ80 magnesium alloy was refined obviously by the low-voltage pulsed magnetic field and significant grain refinement in the DC casting ingot of AZ80 magnesium alloy was achieved. Meanwhile, the morphology of the dentritic in the DC casting ingot was transformed from coarse dentritic to fine rosette with the application of low-voltage pulsed magnetic field. The ability of deformation of the ingot was enhanced and especially the plasticity of the ingot center after upsetting was improved greatly by more than 80% after deformation.
Key words: AZ80 magnesium alloy; DC casting; pulsed magnetic field; grain refinement

1 Introduction

Direct chill (DC) casting is a type of continuous casting developed in the 1930s in Germany and in the 1940s in the USA as an improvement replacing the process of casting extrusion and rolling ingots in permanent moulds [1]. DC casting is a widely used continuous casting process, producing non-ferrous alloy ingots for remelt, extrusion and rolling. Under common DC casting conditions, as-cast structures of magnesium alloys are usually composed of developed dendrites and coarse grains, which results in poor mechanical properties.

Grain refinement of the as-cast magnesium alloys is beneficial not only to the improvement of the strength but to the plastic deformation capacity, which is beneficial to extrusion, rolling and forging of the alloys. Modification by alloying is considered as one of the most effective approaches to refine magnesium alloys. Zirconium is often added into magnesium alloys that contain little (impurity level) or no Al, Si, Mn, Ni and Fe as a potent grain refiner to improve the mechanical properties [2]. Superheating and carbon inoculation have been reported to be effective for Mg−Al alloys [3−5], but it is considered that until to now no effective grain refiner for Mg−Al system alloys can be accepted. It was reported that the rare earth (RE) can refine the grain of metal materials [6−9]; however, the higher cost restricts the application on a large scale. Furthermore, modification by alloying changes the compositions of the alloys. Thus, effective approaches to refine the grain alloys without changing the alloy compositions are expected.

Through extensive studies, it was proved that pulse electric currents were effective approaches to control the solidification process and refine the solidified structure [10−18]. However, until to now, pulse electric current has not been used in industry on a large scale because the application to the melt during solidification is very difficult. Therefore, new approaches should be explored to obtain the refinement grains in the solidified structure for metal materials.

To overcome the drawback of pulse electric current, a new pulsed magnetic field technique is developed to refine the solidified structure, which causes no pollution to the metal melt for there is no contact with metal melt. The effect of strong pulsed magnetic field (SPMF) on the as-cast structure of 2024 aluminum alloy was analyzed [19]. It was found that grains were markedly refined with the application of SPMF. Subsequently, grain refinement was achieved in pure alumina and

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austenitic stainless steel with the application of SPMF [20,21]. Though the grain can be refined by the SPMF, the strong magnetic field is not easy to be controlled and is unsafe to utilize due to the high voltage. Therefore, this technique has not found its industry application on a large scale. It is required to develop more effective and safe techniques to refine the solidified structure of metal materials.

Recently, we have developed a low-voltage pulsed magnetic field (LVPMF) technique to refine the solidified structure of metal materials. Through extensive studies, it was found that significant grain refinement effect in magnesium alloy and superalloy has been obtained [22−28]. This technique opens up a new area of refining metal materials without contamination. LVPMF technique has a great potential to be used on a large scale in industry to refine the as-cast structure of metal materials. The aim of the present work is to study the effects of a low-voltage pulsed magnetic field on the solidified structure and mechnical properties of DC casting AZ80 magnesium alloy.

2 Experimental

Pure magnesium (99.99%), pure aluminum (99.95%) and pure zinc (99.99%) and a Mg−10%Mn master alloy were used in the preparation of AZ80 alloys. Pure magnesium and pure aluminum were melted in a carbon steel crucible under a protective atmosphere of CO_2/SF_6 gas mixture. Pure zinc and Mg−Mn master alloy were added to the molten alloy in the crucible approximately at 730 °C. After 15 min, the alloy melt was stirred to make more homogeneous distribution of the alloying elements, and then refining was operated for 5−10 min with refining flux and high-purity Ar gas, and the melting should be held for 15−20 min before DC casting. DC casting was carried out with a semicontinuous casting machine and the diameter of crystallizer was 208 mm. At the initial stage of semicontinuous casting, the round billet was cast without LVPMF, namely, by the conventional process, when the round billet was about 700 mm in length, the low-voltage pulsed magnetic field generator was promoted, and the round billet was cast under the condition of LVPMF. In order to obtain the best refinement effect, the frequency and voltage of LVPMF were selected as 30 Hz and 200 V, respectively, meanwhile, all the other casting parameters remained unchanged.

The schematic diagram of DC casting under the condition of LVPMF (PM-DC) is shown in Fig.1.

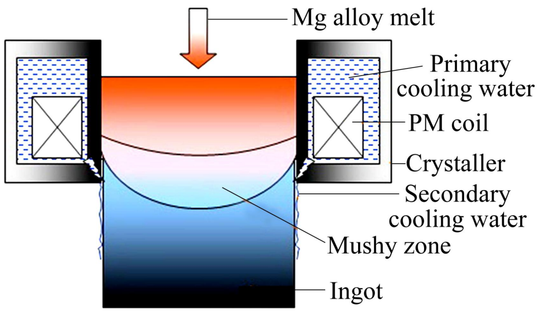

Fig. 1 Schematic diagram of DC casting under condition of LVPMF (PM-DC)

In order to investigate the deformation characteristic of the DC casting and PM-DC casting ingots, the upsetting deformation was conducted by use of forging hammer process, the ingot size before forging is 70 mm in diameter, 107 mm in height, the upsetting slab size is 142 mm in diameter, 26 mm in thickness, and the total deformation is about 70%. The upsetting temperature is 380 °C.

The specimens for microstructrue observation were taken from the cross-section with identical distances of 50 mm ($R/2$) from the edge of the ingot. All samples used for tests were cut from the mid portion of the alloy billets individually, and the samples were ground with SiC paper up to 2500 grit, fine polished using 2.5 μm diamond paste, and each one was etched with a solution of 4.2 g picric acid, 10 mL acetic acid (99%), 10 mL H_2O and 70 mL ethanol (95%, volume fraction).

Optical camera (SONY−T300) and scanning electron microscope (SEM, JSM−6301F) coupled with energy dispersed spectroscopy (EDS) were used to acquire information about the microstructures and morphologies of the alloys.

3 Results and discussion

3.1 As-cast structure

Figure 2 shows the macrostructures of DC casting ingots of AZ80 alloy solidified with or without the application of LVPMF. It is apparent that, when the LVPMF is applied during DC casting, the grains are markedly refined and become more uniform. The macrostructure is composed of coarse grains in the DC casting ingot, and the structure is very nonuniform, as shown in Fig. 2(a). When the LVPMF is applied during solidification, the grains in the PM-DC casting ingot are markedly refined and more uniform, as shown in Fig. 2(b). Based on the results in Fig. 2, it can be concluded that fine and uniform grains during PM-DC casting of magnesium alloys can be obtained.

Figure 3 shows the effect of LVPMF on the dendrite morphology of the DC casting ingots of AZ80 alloy. It is evident that without the application of LVPMF during DC casting, α(Mg) in the microstructure of AZ80 alloy ingot can be characterized by coarse dendrite, as shown in Fig. 3(a), the average grain size is about 1500 μm.

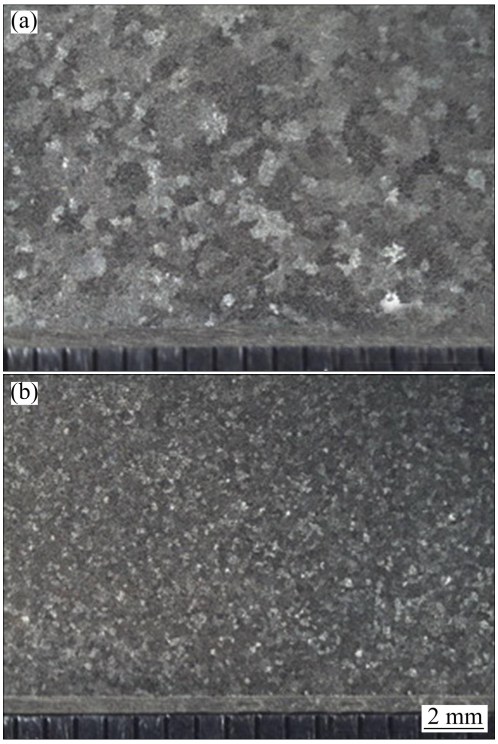

Fig. 2 Macrostructures of DC casting ingots of AZ80 alloy with or without application of LVPMF: (a) DC; (b) PM-DC

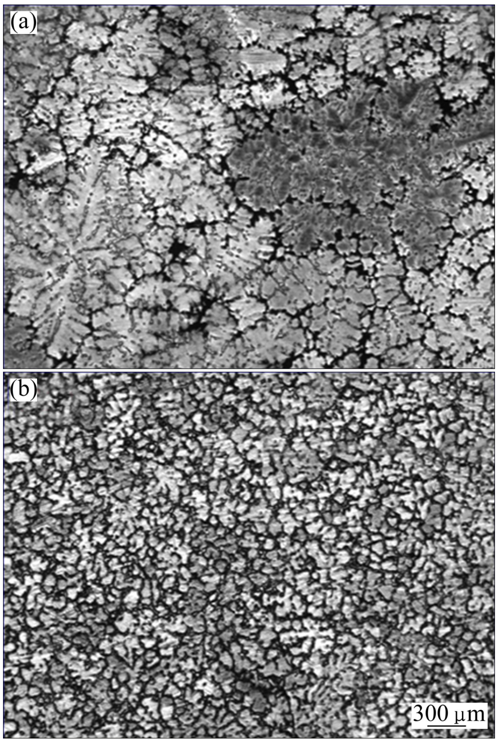

Fig. 3 Microstructures of DC casting ingots of AZ80 alloy with or without application of LVPMF: (a) DC; (b) PM-DC

While the LVPMF is applied, coarse α(Mg) dendrite is refined and the dendrite arm is shortened and becomes more homogeneous, as shown in Fig. 3(b), the average grain size is about 100 μm. From Fig. 3, α(Mg) in the microstructure is transformed from developed dendrites to rosette, which is in favor of the decrease of solute segregation.

Macro segregation of main solute elements Al, Zn and Mn in the ingots of AZ80 alloy is shown in Fig. 4. It can be seen that when the LVPMF is applied, alloying elements distribute more uniformly along the direction of diametric of ingots. Without any application of the LVPMF, the content of solute element Al at the edge of the ingot is high, while the content at core of the ingot is low, which is mainly due to the chilling action of the crucible wall, resulting in slowing the diffusion of the

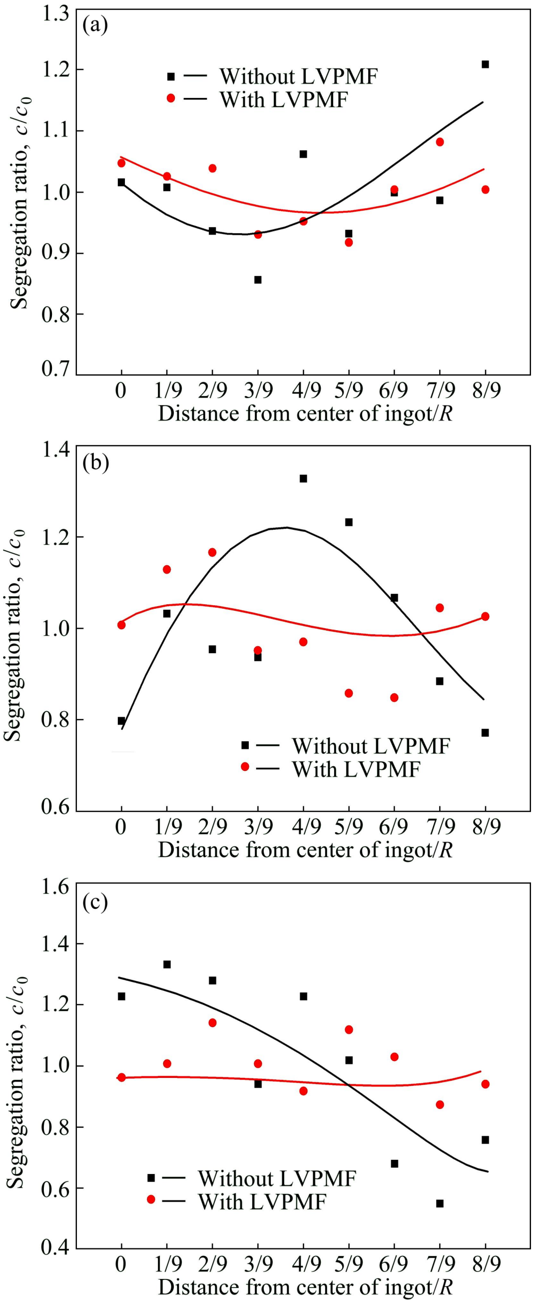

Fig. 4 Macro segregation of main solute elements Al, Zn and Mn in AZ80 alloy ingots : (a) Al ; (b) Zn ; (c) Mn

Al elements near the edge of the ingot, but with the application of the LVPMF, the Al elements are homogeneously distributed over the entire cross section, mainly because of the stirring effect of the pulsed magnetic field, which cause the alloy melt to flow more intensely. The solute enriched melt at the edge will flow into the core of the melt in the crystallizer, and during solidification, the broken dendrite at the edge will flow into the melt inside with melt together. So, the enrichment of Al elements at the solidification interface reduces. The influence law of pulse magnetic field on the macro segregation of Zn and Mn elements is similar with that of Al elements, and the application of the LVPMF can reduce the macro segregation of Zn and Mn elements.

3.2 Deformation characteristic

Figure 5 shows the slabs prepared by forging hammer process. It can be seen that the macroscopic surface of the slabs of the DC ingot is rougher than that of the PM-DC casting ingot, and the severe plastic deformation has been generated in the slabs of the DC ingot, mainly because the grains in the DC ingot are very coarse, which cause the deformation concentrated on the small number of coarse grains, the strain gradient between the grain internal and grain boundary varies greatly, the deformation of single grain is very severe. However, the average grain size of the PM-DC ingot, 100 μm, is about 1/15 of that of the DC ingot. Fine grains can activate the non-basal slip system, and cause grain boundary slipping. In addition, the finer the grain size, the smaller the strain gradient between the grain internal and grain boundary, the more homogeneous the deformation, and the less the opportunity of cracking caused by the stress concentration. The above analysis suggests that, compared with DC ingot, the deformation capacity of the PM-DC casting ingot was improved significantly.

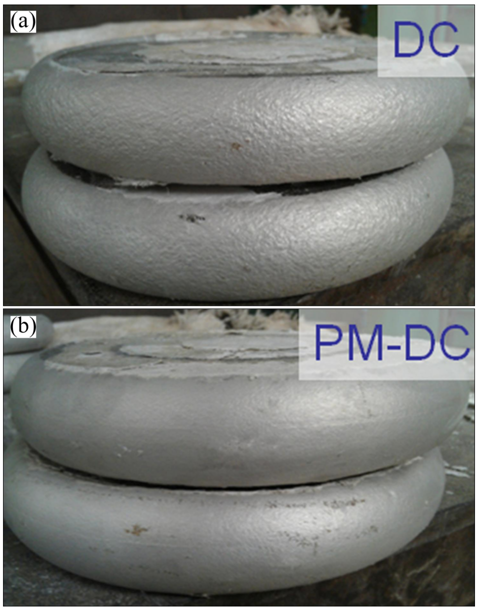

Fig. 5 Slabs prepared by forging hammer process: (a) DC; (b) PM-DC

The deformation microstructures after upsetting of the ingots are shown in Fig. 6. It can be seen that the dynamic recrystallization (DRX) during the deformation occurs in the two kinds of ingot, and the DRX grains are very small; however, the dynamic recrystallization in the DC ingot is not sufficient, probably because, for the DC ingot, the plastic deformation concentrates on the small number of coarse grains under the same stress, and the strain gradient between the grain internal and grain boundary varies greatly, which results in the inhomogeneous plastic deformation occurring in the DC ingot. In addition, from Fig. 6, it is known that the DRX grain size of the DC ingot is bigger than that of the PM-DC casting ingot, which suggests that the initial grain size of the ingots affects significantly on the DRX grain size, this result is consistent with that reported in Ref. [29]. YANG et al [29] researched the recrystallization during and following hot working of AZ31 alloy, they found that the DRX microstructure of Mg alloys was particularly sensitive with the initial grain size, when the initial grain size is larger, the DRX grain size is also coarser, and vice versa.

In order to investigate further the deformation characteristic of PM-DC casting ingots, the hot compression test was conducted at different deformation

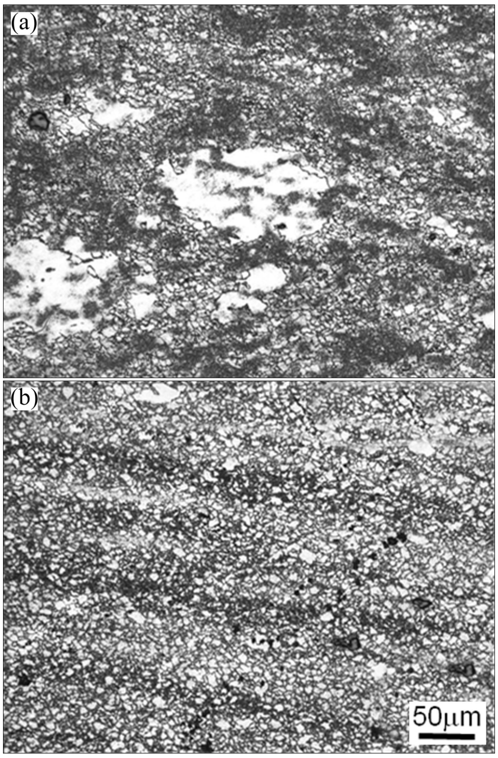

Fig. 6 Deformation microstructures after upsetting of ingots: (a) DC; (b) PM-DC

temperatures by use of thermal simulation machine. Figure 7 shows the hot compression test results of DC and PM-DC casting ingots of AZ80 alloy. From the true stress−strain curves at different temperatures, it is known that homogeneous microstructure with fine grain size in the PM-DC casting ingot causes the time of the work hardening to become shorter, dynamic recrystallization occur quickly, and deformation ability of the ingot to be enhanced.

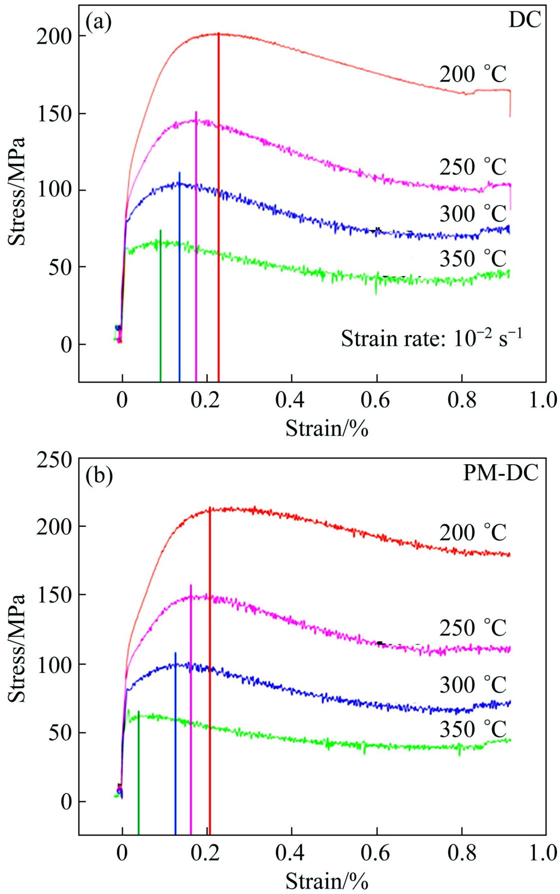

Fig. 7 True stress−strain curves of DC (a) and PM-DC (b) casting ingots of AZ80 alloy at different temperatures

On the basis of the above analysis, it can be concluded that PM-DC casting process is helpful to improve the deformation capacity of the ingot.

3.3 Tensile properties

Table 1 shows the tensile properties of as-upset AZ80 alloy ingot prepared by DC or PM-DC casting process. From the tensile test results in Table 1, it can be seen that, compared with AZ80 alloy ingots prepared by DC process, the AZ80 alloy ingots prepared by PM-DC casting process after upsetting have better tensile properties at room temperature. Especially, the tensile properties of the ingot center are increased significantly, for the as-upset AZ80 alloy PM-DC ingots, the ultimate tensile strength (UTS), yield strength (YS) and elongation (EL) of the center ingot are 329 MPa, 248 MPa and 9%, respectively, which are increased by 7%, 18% and 80% compared with those of AZ80 alloy DC ingots, which are 307 MPa, 210 MPa and 5%, separately. This means that the grain refinement by PM-DC casting process can improve not only the deformation ability, but also the tensile properties of the ingots. Meanwhile, under the same deformation level, the tensile properties of the ingots after upsetting are also increased, which is correspondent with Hall−Petch relation [30]. According to Hall−Petch relation, the finer the grain size, the higher the strength of the alloy. Under the same deformation conditions, the smaller the grain size, the smaller the distance between the grain boundary and the dislocation source, then the smaller the number of dislocations, which lead to the stress concentration arising from the dislocation pile-up group slipping to the grain boundary nearby smaller. Therefore, bigger force is needed to make the plastic deformation of the adjacent grains, which means that the strength of alloy is higher. In addition, grain refinement can improve the ductility and toughness of the alloy, because the strain difference between the interior and the area adjacent the boundaries of fine grain becomes smaller, and deformation becomes more uniform, so the chance of cracking caused by stress concentration becomes smaller. All the initiation and propagation of the crack in the fine grain alloy are difficult, and more energy can be absorbed during the deformation process, which exhibit higher ductility and toughness.

Table 1 Tensile properties of as-upset AZ80 alloy ingot

Sample	Location	UTS/MPa	YS/MPa	EL/%
DC ingot	Center	307	210	5
	1/2 radius	330	270	8
PM-DC ingot	Center	329	248	9
	1/2 radius	345	260	11

In order to investigate the deformability of the DC and PM-DC casting ingots, the extrusions of the AZ80 ingots are conducted, and the tensile properties of as-extruded AZ80 alloys are tested. The tensile properties of as-extruded AZ80 alloy fabricated with DC and PM-DC casting process are shown in Fig. 8. From the tensile property test results, it is apparent that the tensile properties of as-extruded AZ80 alloy from the PM-DC casting ingot are better than those of as-extruded AZ80 alloy from the DC casting ingot. The ultimate tensile strength (UTS), yield strength (YS) and elongation (EL) of the as-extruded AZ80 alloy by PM-DC casting process are 333 MPa, 266 MPa and 17% separately, while the UTS, YS and EL of as-extruded AZ80 alloy by DC casting process are 300 MPa, 210 MPa and 15%, respectively. The UTS, YS and EL are enhanced by about 11%, 27% and 13%. This result also suggests that the PM-DC casting process can improve not only the deformation performance of the ingots, but also the tensile properties of the ingots after deformation.

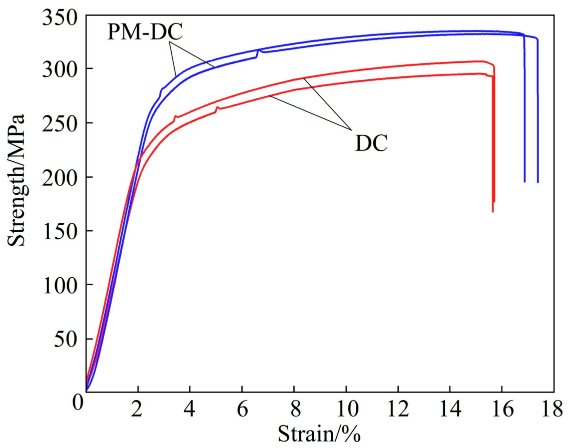

Fig. 8 Tensile properties of as-extruded AZ80 alloy

4 Conclusions

1) A new processing combined a low-voltage pulsed magnetic field with DC casting (PM-DC casting) is developed to refine DC casting ingot grains of magnesium alloy, and fine and uniform grains can be obtained. α(Mg) in the microstructure is transformed from developed dendrites to rosette, which is in favor of the decrease of solute segregation.

2) The PM-DC casting process can help to improve the deformability of the ingot. And the dynamic recrystallization can occur more easily in the ingot and the dynamic recrystallization is more sufficient.

3) Compared with DC casting ingots, the PM-DC casting ingots after upsetting have better tensile properties at room temperature. Especially, the tensile properties of the ingot center are increased significantly. The ultimate tensile strength (UTS), yield strength (YS) and elongation (EL) of the center ingot are 329 MPa, 248 MPa and 9%, respectively, which are increased by 7%, 18% and 80% compared with those of AZ80 alloy DC ingots, which are 307 MPa, 210 MPa and 5%, separately.

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低压脉冲磁场半连续铸造 AZ80 合金组织及力学性能

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摘　要：研究低压脉冲磁场对半连续铸造 AZ80 镁合金凝固组织及性能的影响。结果表明：低压脉冲磁场半连续铸造 AZ80 合金凝固组织发生了明显的细化，枝晶形貌由粗大的枝晶变为细小的蔷薇状。AZ80 半连续铸锭的变形能力大大提升，相比未施加脉冲磁场制备的 AZ80 半连续铸锭，其心部变形后塑性提高了 80%以上。

关键词：AZ80 镁合金；DC 铸造；低压脉冲磁场；晶粒细化

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