Recent Developments and Prospects on the Research and Application of Cast Magnesium Rare-Earth Alloys

Guohua Wu, Xin Tong, Wenjiang Ding
National Engineering Research Center of Light Alloy Net Forming and State Key Laboratory of Metal Matrix Composites,Shanghai Jiao Tong University, 800 Dongchuan Road, Min Hang, Shanghai, China
*Corresponding address: e-mail: ghwu@sjtu.edu.com

Abstract: Magnesium (Mg) alloy exhibits the characteristics of low density, high specific strength and stiffness, good damping capacity, etc. The addition of rare earth (RE) elements can effectively improve the creep resistance and corrosion resistance of Mg alloys, showing broad application prospects in aerospace, national defense, and military industries. This report systematically reviews the latest research progress of high-performance casting Mg-RE alloy materials. Based on the alloy characteristic, a comprehensive summary of the progress of the melt preparation of high-quality Mg-RE alloy is provided from the perspective of melt purification and grain refinement, and the impact of melt treatment on the preparation quality of Mg-RE alloys is discussed. Various kinds of casting processes of Mg-RE alloys are summarized, and the key technical difficulties and countermeasures in the casting and repair welding processes of Mg-RE alloys are concluded. Finally, the practical engineering applications of Mg-RE alloys in aerospace and other fields are introduced, and the key problems and development trends of Mg-RE alloy casting are prospected.

Keywords: Mg-RE alloys, high-performance, melt preparation,casting processes, application

Introduction

In recent years, magnesium rare earth (Mg-RE) alloys have received increasing attention because of their low densities, high specific strengths and creep resistances, good ignition-proof performance, and corrosion resistance, which exhibits wide application prospects in aerospace, military industry, railway, and 3C products. In comparison with other traditional magnesium alloys (Mg-Al, Mg-Zn alloys, etc.), Mg-RE alloys show different characteristics, which bring completely different alloying strategies, melt preparation, casting processes, and application scenarios [1]. For instance, precipitation strengthening contributes the most to the strength of cast Mg-RE alloys, so its alloying strategy should be developed based on a promoted aging precipitation behavior. The melt treatment (including purification and grain refinement) of Mg-RE alloys is more complicated since both the loss of RE elements with high chemical activities and the settling of the heterogeneous nucleation site of Zr should be given extra consideration. The die-casting process commonly used for Mg-Al alloy is not suitable for Mg-RE alloy, because it is difficult for the die-cast Mg-RE alloy to reach its full potential on precipitation strengtheningthrough heat treatment. Moreover, in the actual production, the repair welding of cast Mg-RE alloys is urgently required because casting defects are inevitable even in an upgraded casting process. Based on the above analyses, this paper summarizes some noteworthy aspects related to the cast Mg-RE alloys including alloy development, melt preparation, precision liquid processing, repair welding, and some practical applications.

Development of Mg-RE casting alloys

High-strength Mg casting alloys are generally considered to be alloys with tensile strength above 350 MPa, and they are mainly Mg-Gd series alloys with a high total RE content. The high-strength Mg-Gd alloys can be further divided into Mg-Gd-RE-Zr,Mg-Gd-Zn-Zr, Mg-Gd-Ag-Zr, Mg-Gd-RE-Zn-Zr, Mg-Gd-RE-Ag-Zr series. In the peak-aged Mg-Gd-RE-Zr alloys, the nanoscale β' precipitates with dense distribution are considered as the key strengthening phase, while some researchers also suggest that the coexistence of β''+β' or β'+β_1 leads to the peak aging response. The β' phase precipitated in a triangular arrangement on $\{11\text{-}20\}_{\alpha\text{-Mg}}$ prismatic planes can serve as effective barriers to the basal dislocation slip, resulting in higher strength. The addition of Zn or Ag to Mg-RE series alloys can further promote the precipitation strengthening effect due to the introduction of the basal precipitates γ''. It has been reported that the cast Mg-15.6Gd-1.8Ag-0.4Zr exhibits an extremely high tensile strength of 423 MPa with an elongation of 2.6% [2].

Meltpreparation of Mg-RE alloys

The melt treatment is one of the key processes to determine the service performance of cast Mg-RE alloys, including grain refinement and melt purification.

Zr is the most effective grain refiner for casting Mg-RE alloy, which is always introduced into the melt by Mg-Zr master alloy. The existence type (undissolved particle or dissolved solute) and distribution of Zr within the melt have significant impacts on grain refinement efficiency [3]. Large plastic deformation and high-frequency re-melting were used as pretreatments to break up Zr clusters and increase the number of effective Zr nuclei in Mg-Zr master alloys. Moreover, it was found that the external electrical or ultrasonic field can also promote the dispersion and dissolution of Zr in the melt, resulting in a higher grain refinement efficiency.

The purification of Mg-RE alloy melt can be divided into flux purification, non-flux purification (e.g., filtration, gas bubbling), and compound purification. Up to now, flux purification is still the most effective and widely used method for Mg-RE alloys in industry. However, the RE elements usually react with $MgCl_2$ in the flux and cause RE loss. A new type of flux containing $RECl_3$ has been developed to reduce the RE loss. Moreover, it has been reported that both purification and grain refinement of Mg-RE alloy can be realized in only one step by flux refining using a new compound flux composed of $ZrCl_4$ and JDMJ purifying flux, and the melt preparation process is significantly simplified.

Casting process for Mg-RE alloys

The casting methods of Mg-RE alloy components include high-pressure die casting, low-pressure casting, squeeze casting, semi-solid forming, etc. Different casting methods contain different temperature distributions, solute fields, and melt flows during solidification, which plays an important role in the alloy microstructure. For example, die-cast Mg-RE alloy involves an extremely fast cooling rate, containing a grain size of only 3~10 μm. However, the properties of die-cast Mg-RE alloys cannot be further improved by heat treatments. The internal quality of low-pressure casting and squeeze casting of Mg-RE alloys is higher, so the advantages of aging hardening of Mg-RE alloys can be exerted by heat treatments. In practical production, the large-scale Mg-RE alloy components with complex structures used in aerospace are usually fabricated by a low-pressure sand-casting (LPSC) process. For instance, the thin-walled Mg-RE castings with a length of 1700 mm and thickness of 2 ~ 5 mm were successfully fabricated by LPSC [1]. The antigravity melt flow and applied pressure during solidification are beneficial to the surface quality, dimension accuracy and reduced shrinkage porosity.

Repair welding of Mg-RE alloy castings

In actual production of Mg-RE alloy castings, repair welding technologies is usually used to remove the casting defects, exhibiting significant value in reducing the rejection rate and production cost. Various welding methods including tungsten inert gas (TIG) welding, laser beam welding, and friction stir welding have been studied for repairing Mg-RE alloy castings. The casting defects are often located in complex structures such as reinforcing rib and lug boss, thus the TIG repair welding with good operability is the main method used in actual applications. However, it was found that abnormal grain coarsening is usually occurred in the TIG-repaired Mg-RE alloys during the conventional post-weld solution treatment, which can be alleviated by using pre-weld solution treatment or progressive post-weld solution treatment. After heat treatment, the joint efficiency of TIG-repaired Mg-RE alloy can reach up to 80%, and the elongation is even higher than that of the base material.

Applications of Mg-RE alloy castings

Mg-RE alloys have the characteristics of light weight, high creep resistance, good damping capability as well as good castability. Therefore, Mg-RE alloy castings are widely used in aerospace and aviation industries, weapon and defense industries, transportation and other civil fields. For instance, commercial Elektron® 43 (WE43C) and Electron® 21 (EV31A), are firstly been accepted for applications in jet engines and military aircrafts. Now, the Mg-RE alloy castings are also used as aircraft seats, shell of the reduction gearboxes, light missilescabin, radar components and car engine block.

Conclusion

This paper reviewed the recent developments of high-performance Mg-RE casting alloys, especially on alloy design, melt preparation, precision liquid processing and repair welding techniques, and engineering applications.

References

[1] Wu G H, Wang C L, Sun M and Ding W J.Recent developments and applications on high-performance cast magnesium rare-earth alloys. J. Magnes. Alloy., 2021, 9(1):1-20.

[2] Zhang Y, Wu Y J, Peng L M, Fu P H, Huang F and Ding W J.Microstructure evolution and mechanical properties of an ultra-high strength casting Mg–15.6Gd–1.8Ag–0.4Zr alloy.J. Alloy. Compd., 2014, 615:703-711.

[3] Wu G H, Tong X, Wang C L, Jiang R and Ding W J.Recent advances on grain refinement of magnesium rare-earth alloys during the whole casting processes: A review. J. Magnes. Alloy., 2023, 11(10):3463-3483.