Magnesium: Structure and Properties

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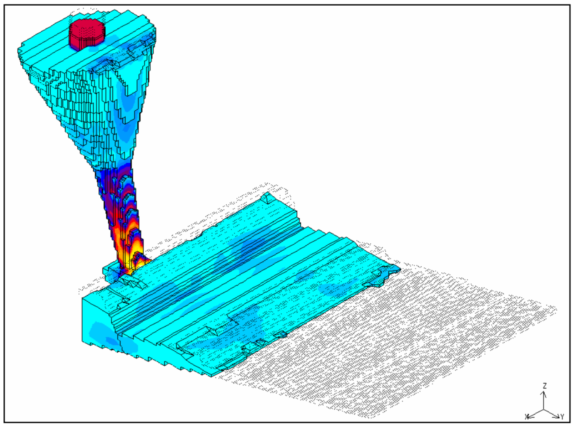
Introduction

The purpose of this paper is to get a good knowledge of how cooling conditions affect the solidification structure of the magnesium alloy AZ91. It is well known that microstructure of an alloy is controlled by the heat flow during casting. Changes in the heat transfer coefficient of the casting affect the heat flow and the temperature distribution.

For the same geometry, by using different mould materials, it is possible to get different cooling conditions during the solidification process, if each mould has a different ability to extract heat. Given that, it is expected that silica sand mould and copper mould leads the magnesium alloy castings to different cooling conditions during the solidification. Copper mould and silica sand mould were preheated prior to casting to show

In order to obtain representative conditions and broader data, part of the work deals with a geometry that consists of a plate with three different thickness, while the other part deals with three tensile bars with different sections, to find out different cooling conditions related with thickness and sections differences for the same mould material.

The preliminary part of the work included design and optimisation of the casting, runners, and gating system, this process was carried out by a series of trials, as well as several numerical simulations and analysis of filling and solidification of the casting.



The solidification process was analysed through the casting experiments. Thermocouples were connected to a computer-aided thermal analysis able to trace thermal curves, including heating and cooling curves.

The numerical simulation software is considered to have high accuracy although it is expected to find evident differences between the results obtained by the numerical simulation and those obtained by the use of thermocouples in the castings during the experiments. The second group of casts is related with this, the corresponding numerical simulations were done in order to find similarities and /or differences between the results of the casting experiments and the numerical simulations.

The metallographic analysis was carried out by the analysis of the micrographs acquired from the Optical Microscope. Simultaneously the samples were analysed by a Scanning Electron Microscope and X-Ray Diffraction, in order to get a confirmation of the results got from the Optical Microscope.

The relation between results from the metallographic analysis, by the Scanning Electron Microscope and the X-Ray Diffraction were compared with the results got from previous thermal analysis and those from the numerical simulations. The subsequent discussion was based on these results and their comparison with the theoretical basis.

History

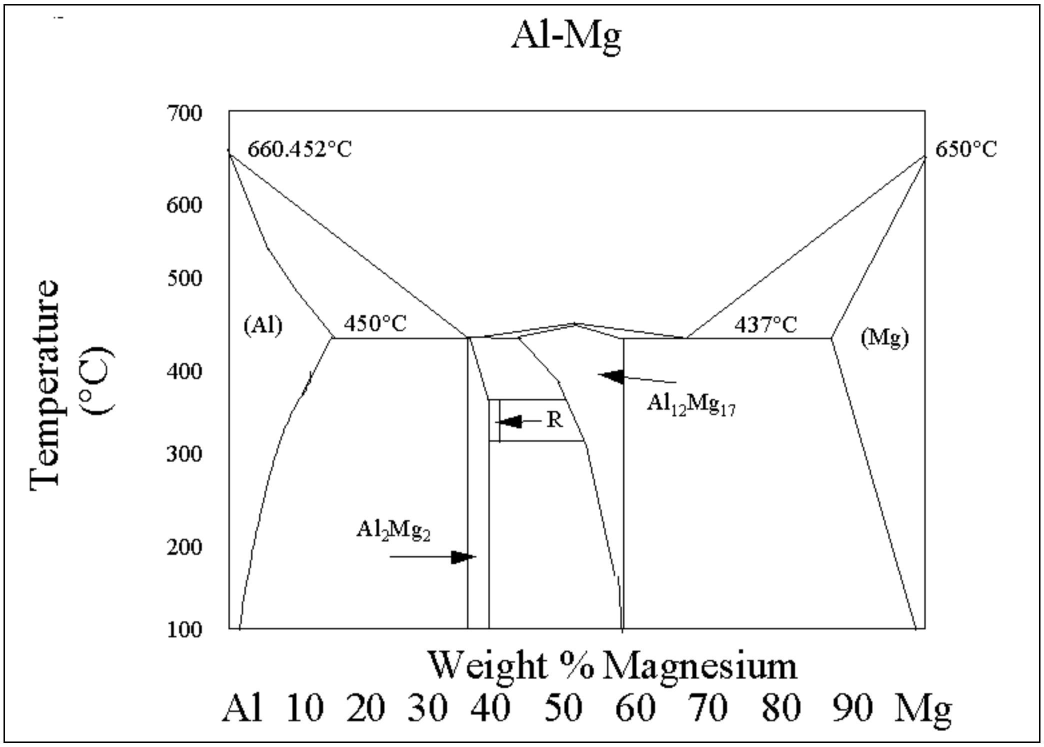
Sir Humphrey Davy was the first to produce magnesium of acceptable purity in 1808 from a magnesium amalgam. The first industrial production of magnesium took place in 1886 at the Aluminium-Magnesium Factory at Hemelingen, where the metal was obtained through the electrolysis of molten carnallite. Griesheim Elektron at Stassfurt, Germany, built the first commercial magnesium plant in the same year.

Magnesium was first introduced as a structural material in 1909, although by the turn of the century the entire world production was only 10 metric tons per year [IMA]. Mg-Al-Zn castings were used extensively in Germany during the First World War. In 1925, a serious corrosion problem of Mg-Al-Zn alloys was overcome by the discovery that small addition (0.2%) of manganese increased the corrosion resistance. Alloys based on the Mg-Al-Zn system have remained the principal magnesium casting alloys for use at ambient temperatures.

Due to the good physical and mechanical properties, magnesium alloys are being utilized in a growing number of structural applications. For example, the tonnage of magnesium alloys die castings produced in the United States increased from 3,800 metric tons in 1982 to 8,900 metric tons in 1986 [Liu-Ying Wei, 1990]. Global production of Mg alloys die-castings was 70,000 metric tons in 1998 and is projected to be over 230,000 metric tons by 2008 [Fink, 1999].

Properties

Magnesium has a hexagonal crystal structure, and because of a favourable size (atomic diameter 0.320 nm), its alloying behaviour is characterized by an ability to form a solid solution with a variety of elements, particularly those are of commercial importance, including aluminium, zinc, cerium, silver, thorium and zirconium.



The hexagonal closely packed structure and a large and variable grain size have led to less than optimum mechanical properties. Development of alloys to compete more effectively with wrought aluminium alloys has suffered from a substantial difference in the understanding of the phase occurring in magnesium alloys compared to aluminium alloys [Eliezer et al. 1998].

Another important factor in the behaviour of magnesium is the corrosion behaviour. The electrode potential of magnesium places it high in the electrochemical series. The $Mg(OH)_2$ film which forms, while offering protection in rural environment, is nonadhering. Problems also occur with galvanic corrosion requiring protection concepts can alleviate these concerns [Eliezer et al. 1998]

While magnesium alloys generally exhibit good corrosion resistance during atmospheric exposure, their susceptibility to corrosion in chloride environments has been a serious practical limitation to wider application of these alloys. Magnesium is at the active end of galvanic series, a galvanic corrosion is an ever existing threat. Moreover, magnesium oxide is not thermodynamically stable in neutral environments. In spite of these limitations, significant improvements have been made during the past decade in the corrosion resistance of alloy AZ91 by reducing the heavy metal impurity level (Fe, Ni, and Cu), alloying with manganese (0.2 wt %) and heat treatment [Eliezer et al.1998]. A new term “high purity” was introduced to describe alloys with low content impurities like iron, nickel and copper, in the early 1980s.

General Characteristics of Magnesium

In fact, magnesium is rarely used for engineering applications in unalloyed form. Its main use so far is as an alloying addition to aluminium alloys. Other major utilization includes desulphurization of steel, the production of ductile iron and as structural material [Eliezer et al. 1998]. Although most magnesium still serves in aluminium products, engineers have called more frequently on magnesium alloys in the last 20 years, as they rediscover the metal as a structural element on its own right [Erickson and Soper, 1995].

Magnesium alloys are enjoying rapid growth. The primary reason for this is the lightness of magnesium, one-third lighter than aluminium, three-quarters lighter than zinc and four-fifths lighter than steel, being the lightest of all of these, magnesium has also the highest strength to weight ratio of all commonly used metals [Henry Hu and Alfred Yu, 2001].

Magnesium also has a number of desirable features including good ductibility and excellent castability.

The many merits of magnesium attract the use of this material in many structural applications as automotive, aerospace, material-handling, and electronic industries. Applications range from disk drives and other electronic components, steering wheels, instrument panels, and a variety of housing and brackets, to bicycle frames, archery bows, and power tools.

For example, the application of magnesium on the automobile industry drives to a reduced automobile weight that can give in terms of improved fuel consumption.

However, there are some negative features including high reactivity in the molten state, inferior fatigue and creep compared to aluminium and a very bad galvanic corrosion resistance, a limited supply base, a lack of fundamental knowledge of the behaviour of magnesium alloys, and a cost that is about twice that of aluminium [Eliezer et. al. 1998]. Is also known that Mg-Al-Zn alloys show some susceptibility to micro porosity but otherwise have good casting qualities. Some bibliography also refers that Mg-Al system may be prone to micro shrinkage and care must be taken to achieve consistent quality.

The cast Mg-Al-Zn alloys are unsuitable for use at temperatures up to 110-120°C above which creep rates become unacceptable. This behaviour is attributed to the fact that magnesium alloys undergo creep mainly by grain boundary sliding at the phase $Mg_{17}Al_{12}$.

The corrosion resistance of this alloy is a threat and is adversely affected by the presence of cathodic impurities such as iron and nickel and, for some purposes; strict limits have been placed on these elements, though corrosion resistance is generally satisfactory.

Alloy AZ91 (Mg-9Al-0.8Zn-0.2Mn) is the most favoured magnesium alloy, being used in approximately 90% of all magnesium cast products. It has excellent cast ability, sound room temperature mechanical properties and low cost. However, it suffers from low creep resistance at temperatures in excess of 120°C that make it unsuitable for many of the components in automobile engines.

Alloy AZ91 is often alloyed with manganese because, when added in small amounts (fraction of a percent), manganese in general improves the corrosion resistance of magnesium alloys. In absence of manganese, all iron precipitates as Al_3Fe. When manganese is added, several types of inter metallic phases can appear in the Al-Mn-Fe series depending on the method of alloying.

Solidification of magnesium

From the thermodynamic point of view, solidification needs a flux of heat from the melt to the evolving system. During this transference of heat the atoms assumes new positions regarding the structure of the precipitate phases. If the melt is from a pure metal, the movement of the atoms is shorter than the one verified for alloys. For alloys the process evolves mass transference controlled by diffusion.

Like chemical reactions, phase transformations are driven by thermal fluctuations and can only occur when the transfer of atoms from the parent phase to the product phase is higher than the dissolution process [Kurz and Fisher]

The alloys do not solidify as pure metals, alloys solidify over a range of temperatures. Below the temperature at which the alloy begins to solidify and the temperature when it is completely solidified the alloy is in an intermediate state and gradually becoming completely solid as the lower limit of the solidification range is approached.

Therefore for any alloy there is a definite temperature at which solidification begins and an equally definite point where it ends. These two points are known as the Liquidus Temperature and Solidus Temperature. Two metals may be alloyed in many different compositions. It means that it is possible to have 80% A and 20% B or 60%A and 40% B as long as the cooling curves for all these alloys will be different.

All alloys have Liquidus and Solidus Temperatures with the exception of the Eutectic Alloys. This alloy has only one single temperature of transformation where it goes directly from a liquid to a solid state.

The predicted solidification behaviour of magnesium is based on the equilibrium phase diagrams; if the expected sequences of transformations as well as the critical transformation temperatures are provided by these phase diagrams.

However, it is known that different mould types generate different cooling rates (silica sand, zirconium sand and copper mould generate different cooling rates), and between these variety of cooling rates it is expected to find non-equilibrium conditions during the solidification, which means that if the casts are solidified, it will be obtained a different structure for the castings from the predict by the analysis of the phase diagrams.

A series of experiments were conducted in the foundry shop of Department of Manufacturing Engineering, DTU to check the cooling curves of different mould types using the same alloy. Results of these experiments were very interesting theoretically and practically.