An Investigation into Creep-Resistant, As-Cast Magnesium Alloys Containing Yttrium, Zinc, Neodymium and Zirconium

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The steady-state creep rates of a large number of as-cast Mg-Y-Zr alloys containing different Zn and Nd additions were measured at temperatures ranging from 250 to 350 °C. Optimum creep resistance of these alloys was obtained when small additions of Zn and Nd were made, these small additions producing relatively large improvements in the creep resistance.

Following the determination of the magnesium-yttrium phase diagram and the observation of the extensive solid solubility of yttrium in magnesium together with its large temperature dependence, a number of workers have investigated the possibility of producing commercial creep-resistant magnesium alloys based on the magnesium-yttrium system and containing other associated alloying additions. In this present work, the creep resistance of a number of different as-cast magnesium alloys containing nominally 1, 3, and 5 wt pct yttrium with additions of zinc, neodymium and 0.6 wt pct zirconium is reported. For clarification, the possible permutations and nominal amounts (wt pct) of the alloying additions that have been investigated are shown below.

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\begin{align*}
1 \text{ pct Y} & \quad 2 \text{ pct Zn} & \quad 2 \text{ pct Nd} \\
Mg & + 3 \text{ pct Y} & + 4 \text{ pct Zn} & + 4 \text{ pct Nd} & + 0.6 \text{ pct Zr} \\
5 \text{ pct Y} & \\
\end{align*}
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It is noted, that the purpose of the zirconium addition in these, as in most magnesium alloys, is that of a general grain refiner.

EXPERIMENTAL PROCEDURES

All the alloys used in this work were prepared in the Metals Development Foundry at Magnesium Elektron Ltd., Manchester, and were made by melting together 99.98 pct magnesium and an antioxidizing flux in a steel crucible. Alloying additions were subsequently made and the melt stirred and then settled before being cast at 780 °C into square section, horizontal, “finger-bar” molds.

The compositions of all the alloys used were spectrographically analyzed by Magnesium Electron Ltd., and also by Link Systems Ltd. using their SEM analysis system. Good agreement was obtained between these two methods and alloy additions were found to be within 10 pct of the given nominal values.

In order to obtain the average as-cast grain size, finger-bars from each as-cast alloy were polished along their length and then etched in a 1 pct-HNO\(_3\) + H\(_2\)O solution. Little variation in grain size was observed along the length of the bars or across their diameters and typical grain sizes and microstructures are shown in Fig. (1).

Figure 1(a) shows the microstructure of the as-cast Mg-3 pct Y-Zr alloy and is representative of the three as-cast Mg-Y-Zr alloys discussed later, all of which had a measured ASTM nominal grain size of 6. The dark spots in the microstructures of these alloys have been identified as Zr-rich clusters.

Figures 1(b) and (c) show the microstructure of the as-cast Mg-3 pct Y-2 pct Zn-2 pct Nd-Zr alloy and are representative of both the as-cast Mg-Y-Zn-Nd-Zr and the as-cast Mg-Y-Zn-Zr alloys. For both these alloy systems the as-cast structures appear to be two-phase, and are comprised of a) a light-colored Mg-Zr matrix containing occasional Zr-rich clusters and b) a eutectic grain boundary second phase which after examination has been seen to contain practically all of the extra alloying elements (i.e. yttrium, zinc and neodymium or yttrium and zinc). For both these two-phase alloy systems an ASTM nominal grain size of 7 has been measured for the Mg-Zr matrix grains.

From each cast finger-bar two creep specimens could be machined, these specimens having a 25.4 mm gage length and a 4.54 mm diam. Using these specimens creep measurements were carried out using constant stress “Andrade Cam” type machines, each of which had a three-zone furnace which maintained a gradient free temperature along the total length of the specimen to within ± 0.5 °C. Specimen extensions were measured with extensometers using capacitive transducers which were capable of measuring extensions of the order of 1 μm.

CREEP RESULTS AND DISCUSSION

To obtain the creep results that are shown in Figs. 3, 4 and 5 specimens were initially heated to a constant temperature and then loaded. Subsequent time-strain curves were produced and the specimen was kept in the initial constant temperature-constant stress state until a prolonged steady-state creep region was measured. The specimen temperature was then slightly increased and, as a result, a second time-strain curve was obtained which showed both primary and secondary creep regions. The specimen temperature was increased in this way until the time-strain curve showed that the specimen had entered a region of tertiary creep. A typical time-strain curve obtained for a Mg-3 pct Y-2 pct Zn-2...
pct Nd-Zr as-cast alloy is shown in Fig. 2. This curve shows three temperature increases. For clarity, at each temperature increase, the curve is shown displaced back to the strain axis.

As-cast Mg-Y-Zr alloys containing 1, 3 and 5 pct yttrium and 0.6 pct zirconium were initially investigated, and for these as-cast alloys the steady-state creep rates were measured for the temperature range 250 to 300 °C using a constant applied stress of 40 N mm⁻². The results from these experiments (shown in Figs. 3, 4 and 5 in the form of Arrhenius plots of steady-state creep rates vs 1/T) establish that only one creep mechanism is operative over the temperature range considered. Furthermore, it can be seen from the creep curves obtained that no significant difference was measured in the steady-state creep rates for the three different yttrium containing alloys. For example, the steady-state creep rates of all three as-cast alloys at 275 °C are shown to be contained within the range 1.8 - 3.5 · 10⁻⁷ s⁻¹. At higher temperatures however, a decreasing creep rate was measured with increasing yttrium content.

The maximum solubility of yttrium in magnesium is reported to be about 12 pct at 567 °C, and it has further been shown that small additions of zirconium decrease this maximum solubility very slightly. Of relevance to the potential creep resistance of Mg-Y-Zr alloys is the work of Mizer and Peters, who have observed an age hardening response in a Mg-8.7 pct Y alloy. After solution treating and quenching, they found a substantial hardening response (720 N mm⁻² increasing to 920 N mm⁻²) for aging temperatures of up to 200 °C, and attribute this hardening response to the formation of a coherent, metastable second phase that at higher temperatures becomes unstable and rapidly disappears. As a result, specimens hardened at 200 °C rapidly lose their hardness when further aged at 260 °C.

Following the work of Mizer and Peters, specimens from as-cast Mg-Y-Zr alloys containing 1, 3, and 5 pct...