Mechanical properties of magnesium based amorphous alloys produced by powder metallurgy

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Abstract

The newly developed "clean process" enabled safe atomization and consolidation of fine Mg base alloy powders. Amorphous $Mg_{87.5}Cu_5Y_{7.5}$ and $Mg_{70}Ca_{10}Al_{20}$ powders (smaller than 25 μ m) were extruded at 673 K above T_x. They showed a mixed structure consisting of $Mg_{24}Y_5$+Mg_2Cu and Al_2Ca respectively dispersed in a hcp-Mg matrix. The tensile strengths for the bulk $Mg_{87.5}Cu_5Y_{7.5}$ and $Mg_{70}Ca_{10}Al_{20}$ alloys are 740 MPa and 600 MPa at 298 K respectively which are about twice as high as the highest value for conventional Mg alloys. The high strengths are presumably due to the formation of the fine microstructure consisting of nanoscale intermetallic compound particulates homogeneously embedded in the Mg matrix with a fine grain size. These data allow us to expect that the newly developed Mg-based alloys will proceed hereafter as a new type of high specific strength material.

Riassunto

Il procedimento "pulito", di recente sviluppo, ha permesso la polverizzazione e consolidazione sicura di polveri fini di leghe a base di magnesio. Furono estruse ai 673K sopra la Tx le polveri amorfe di Mg87.5 Cu5 Y7.5 e Mg70 Ca10 Al 20 (< 25 μ m) che dimostrarono una struttura mista formata rispettivamente di Mg24 Y5 + Mg2 Cu ed Al2Ca dispersi in una matrice hcp-Mg. La resistenza alla trazione delle leghe di Mg87.5 Cu5 Y7.5 e Mg70 Ca10 Al20 è di 740 MPa e di 600 MPa rispettivamente a 298K, valori che sono circa due volte più grandi di quello più alto per le leghe di magnesio convenzionali. Tali incrementi sono probabilmente dovuti alla formazione di una microstruttura fine costituita di particolati nanometrici di composti intermetallici omogeneamente distribuiti nella matrice Mg con granulometria fine. Questi dati ci permettono di prevedere che le leghe a base di Mg recentemente sviluppate si presenteranno nel futuro nella veste di un nuovo tipo di materiale ad alta resistenza specifica.

INTRODUCTION

By utilizing the crystallization of an amorphous phase, high mechanical strength is expected to be obtained through the formation of an extremely fine (nanoscale) mixed structure. Based on this concept, the bulky Al-based alloys with nanocrystalline structure have been developed by the high pressure atomization and consolidation techniques. The new Al-based alloys have been reported to exhibit high tensile strength, high elevated temperature strength and high fatigue strength.

Recently, Inoue et al. have found that amorphous alloys with high mechanical strengths are also obtained in Mg-based alloy systems by the melt spinning method. The application of the same sequential processes, which were used for the Al-based amorphous alloys, to Mg-based amorphous alloys is expected to cause the formation of a new type of higher specific strength material. However, since the production of Mg-based alloy powders is quite dangerous, it requires the development of a special atomization technique with an accurate atmosphere control system. This paper is intended to present the feature of a newly developed clean process consisting of high-pressure gas atomization and consolidation equipments for Mg-based amorphous powders, and to examine the microstructure and mechanical properties of the bulky Mg-based alloys produced by the process.

EXPERIMENTAL PROCEDURE

Mg-Cu-Y and Mg-Ca-Al ternary alloys were used because the alloy systems are one of the amorphous Mg-based alloy systems having high glass-forming ability and high tensile strength[1-5]. Fig.1 shows a schematic illustration of the new production system for the amorphous Mg-based powders. 330 g of pre-alloyed ingot was atomized from the temperature range of 923 to 1023 K with argon gas at an applied pressure of 9.8 MPa. In the present equipment, oxygen and moisture components in the argon atmosphere were controlled below 1 ppm, respectively. The powders were collected and sieved under 25 μ m in size. The fine powders were precompacted in a cylindrical Cu can with an inner diameter of 20 mm by using a uniaxial pressing machine and sealed by welding. All the processes were carried out in the same controlled atmosphere in a single chamber. The canned powder was taken out and heated in an electrical furnace at 673 K for 900 s and then extruded to an area reduction in 90 % (ratio 10:1) in a 100-ton extrusion press. The microstructures of as-atomized powders and as-extruded bulk were examined by X-ray diffraction, optical microscopy, DSC and transmission electron microscopy. The tensile strength and elongation were measured at a strain rate of $5.6x10^{-4}$ s^{-1} in a temperature range from room temperature to 573 K by using an Instron-type testing machine. The fracture surfaces were examined by SEM.

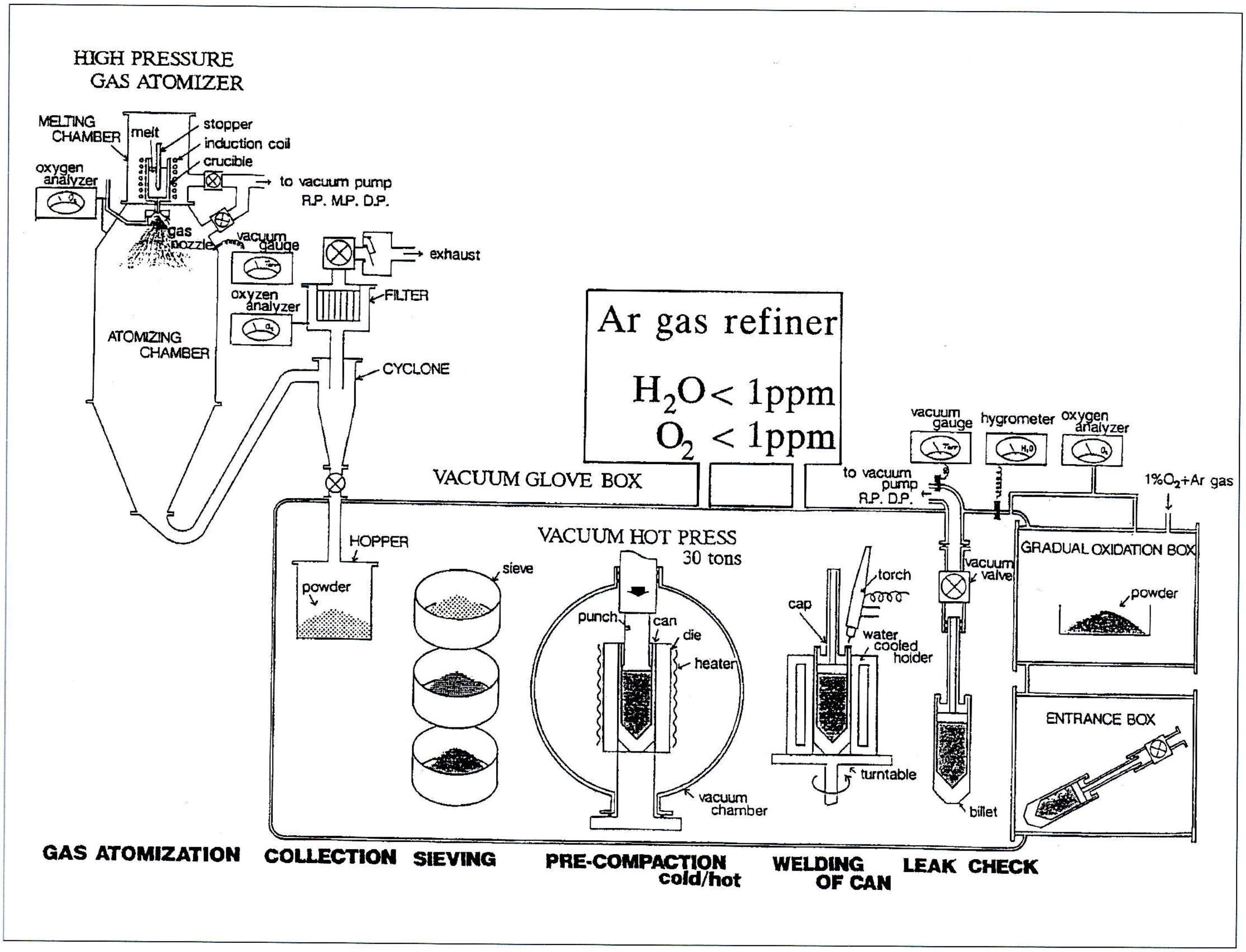

Figure 1: Schematic illustration showing the sequential closed processing system in which the production of atomized Mg-based amorphous powders and their consolidation into a bulk form can carried out in a well-controlled atmosphere

RESULTS

An extremely fine crystalline $Mg_{87.5}Cu_5Y_{7.5}$ and $Mg_{70}Ca_{10}Al_{20}$ alloy were obtained by extrusion of the amorphous powder produced by the clean process at 673 K above T_x with an area reduction of 90 %.

(a) $Mg_{87.5}Cu_5Y_{7.5}$ alloy extruded bulk

Fig.2 shows the X-ray diffraction pattern of the $Mg_{87.5}Cu_5Y_{7.5}$ powders with a particle size fraction less than 25 μ m atomized at 1023 K and of the extruded bulk. The powders are composed of amorphous and hcp-Mg phases, whereas the bulk is composed of hcp-Mg, $Mg_{24}Y_5$ and Mg_2Cu. In order to clarify the microstructure of the extruded bulk, TEM observation was made. As shown in Fig. 3, the structure consists mainly of fine hcp-Mg grains with diameters of 150 to 250 nm. Further detailed analyses indicate that the small precipitates which distribute within the grains are $Mg_{24}Y_5$, while the precipitates along the grain boundaries are mainly composed of Mg_2Cu. Fig. 4 shows the temperature dependence of tensile yield strength ($\sigma_{0.2}$) for the bulk $Mg_{87.5}Cu_5Y_{7.5}$ alloy extruded at 673 K along with the data for a $Mg_{70}Ca_{10}Al_{20}$ alloy and the WE54-T6 (Mg-Y-Nd) alloy. $\sigma_{0.2}$ of the extruded $Mg_{87.5}Cu_5Y_{7.5}$ alloy is as high as 724 MPa at room temperature which is much higher than that ($\sigma_{0.2}$=200MPa) for the WES54-T6 alloy. Although σ 0.2 of the $Mg_{87.5}Cu_5Y_{7.5}$

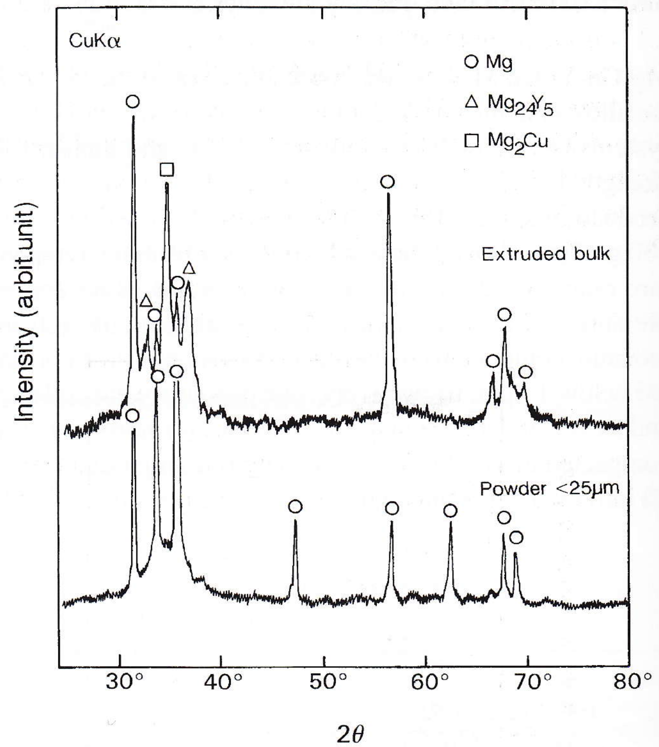

Figure 2: X-ray diffraction patterns of a $Mg_{87.5}C_5Y_{7.5}$ alloy atomized powder and its extruded bulk

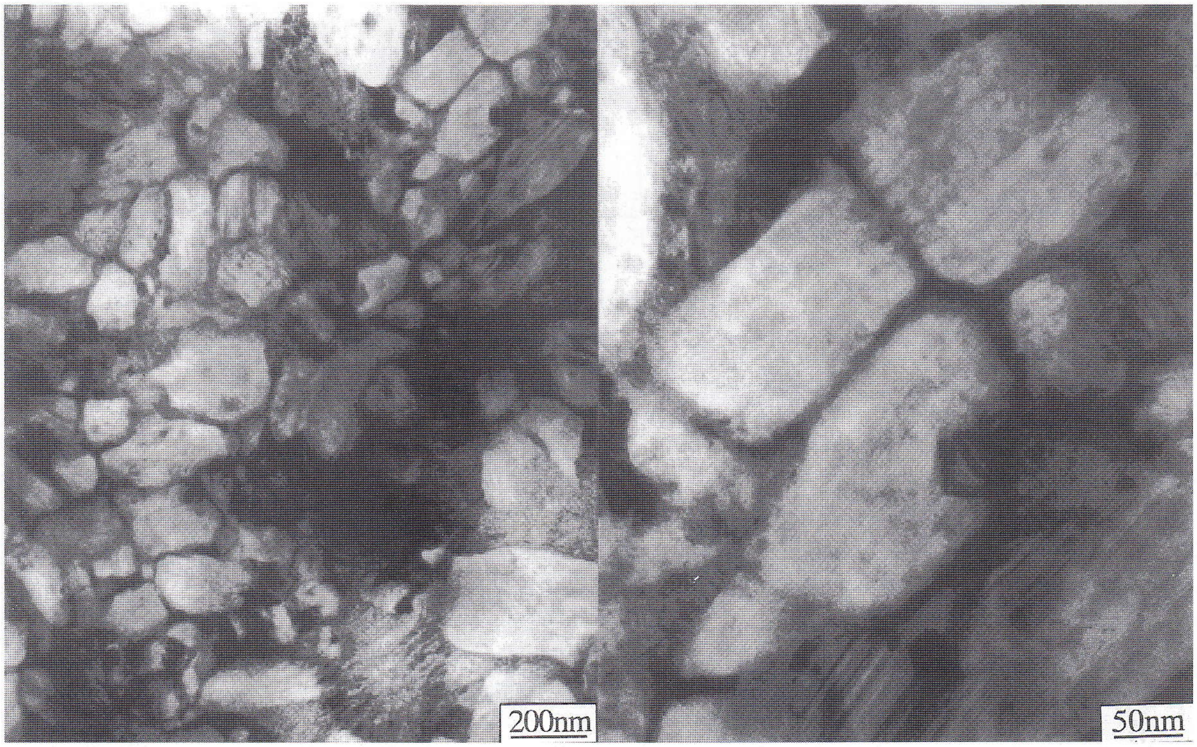

Figure 3: Bright-field electron micrograph of an as-extruded $Mg_{87.5}Cu_5Y_{7.5}$

alloy decreases monotonously with increasing temperature, 0.2 still keeps high value of 640 Mpa at 473 K and then decreases rapidly to 317 MPa at 573 K. The Young's modulus of the extruded $Mg_{87.5}Cu_5Y_{7.5}$ alloy is also as high as 50 GPa which is about 14% higher than that of conventional Mg-based alloys.

(b) $Mg_{70}Ca_{10}Al_{20}$ alloy extruded bulk

The as-atomized $Mg_{70}Ca_{10}Al_{20}$ alloy powder with a particle size fraction below 25 μ m atomized at 1023 K consists of amorphous and Mg phases without any trace of the peaks corresponding to Al_2Ca, as shown in Fig. 5. The as-atomized powder without Al_2Ca is judged to be useful as a raw material for the production of a high-strenght bulk alloy by utilizing the finely mixed structure consisting of fine Al_2Ca embedded in Mg matrix.

Bulk $Mg_{70}Ca_{10}Al_{20}$ alloy was produced by extrusion of the

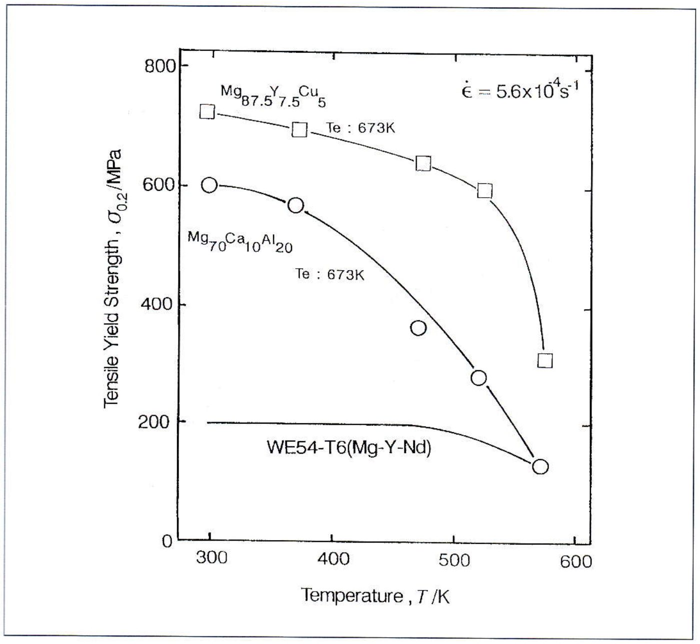

Figure 4: Temperature dependence of tensile yield strengths ($\sigma_{0.2}$) for an as-extruded $Mg_{87.5}Cu_5Y_{7.5}$ alloy and $Mg_{70}Ca_{10}Al_{20}$ alloy obtained by extrusion at 673 K. The data of a commercial WE54-T6 (Mg-Y-Nd) alloy are also shown for comparison

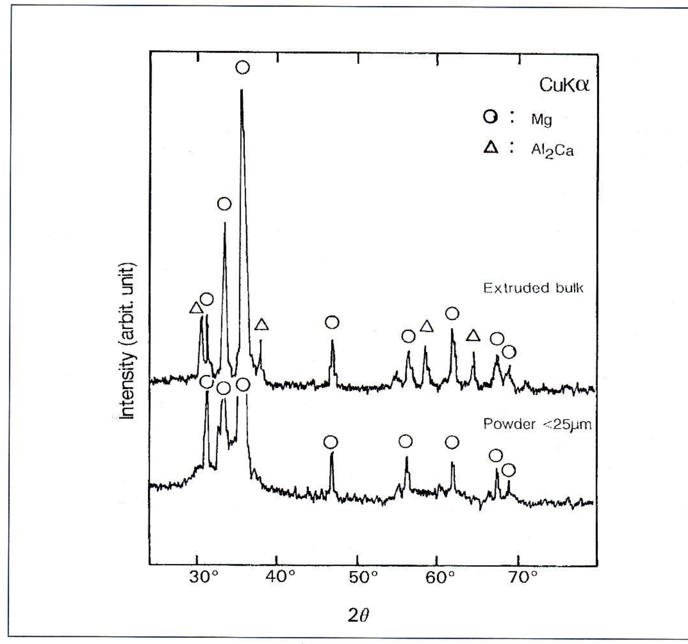

Figure 5: X-ray diffraction patterns of $Mg_{70}Ca_{10}Al_{20}$ alloy atomized powder and its extruded bulk

Figure 6: Bright-field electron micrograph of a bulk $Mg_{70}Ca_{10}Al_{20}$ alloy obtained by extrusion at 673 K

atomized powders at 673 K. All the diffraction peaks in the x-ray diffraction pattern of the bulk are identified to be hcp-Mg and Al_2Ca phases as shown in Fig.5. Furthermore, the bright-field electron micrograph shown in Fig.6 reveals that Al_2Ca compound has a particle size of 75 to 100 nm in the Mg matrix with a grain size of 100 to 200 nm.

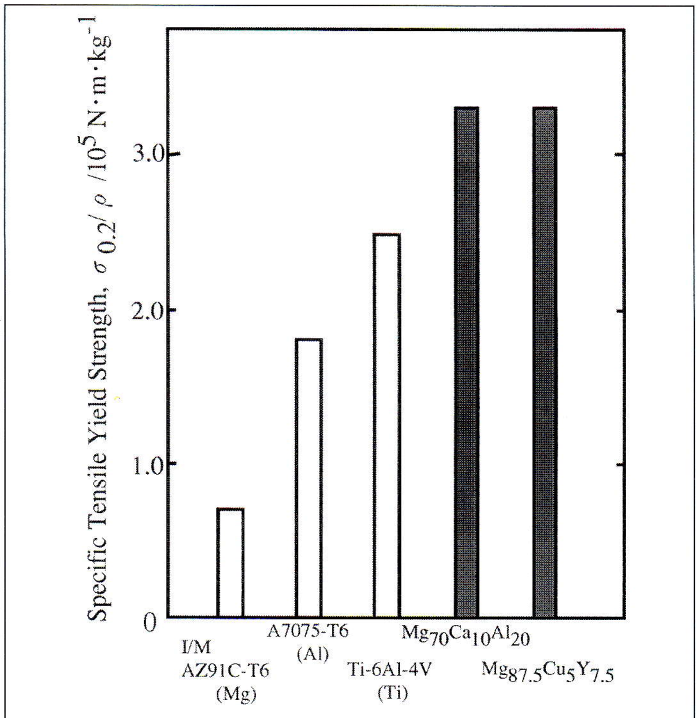

Figure 7: Specific tensile yield strength of a bulk $Mg_{87.5}Cu_5Y_{7.5}$ and a bulk $Mg_{70}Ca_{10}Al_{20}$ alloy obtained by extrusion at 673 K. The data of commercial light weight alloys are also shown for comparison

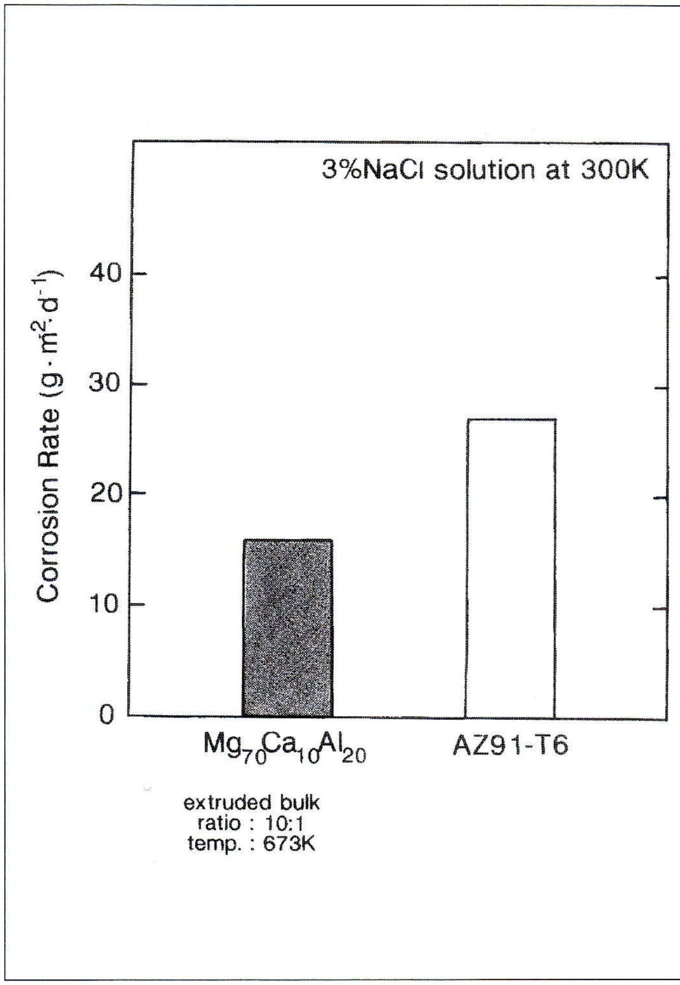

Figure 8: Corrosion rate of a bulk $Mg_{70}Ca_{10}Al_{20}$ alloy obtained by extrusion at 673K. The data of a commercial AZ91-T6 alloy are also shown for comparison

The extruded Mg-Ca-Al alloy tested at RT had a high tensile yield strength ($\sigma_{0.2}$) of 600 MPa and a high Young's modulus of 49 GPa combined with a distinct plastic elongation. The fracture surface of the bulk alloy had a high degree of ruggedness, indicating that a rather large amount of energy was spent for the fracture. The temperature dependence of $\sigma_{0.2}$ for the bulk $Mg_{70}Ca_{10}Al_{20}$ alloy is shown in Fig.4, along with the data for a $Mg_{87.5}Cu_5Y_{7.5}$ alloy and WE54-T6. The Mg-Ca-Al alloy has a high elevated temperature strengths above 300 MPa in the wide temperature range up to 523 K, though the strength level is rather lower than that for the Mg-Cu-Y alloy. The significant increase in the elevated temperature strength is presumed result from the homogeneous dispersion of a large amount of fine Al_2Ca compound. The specific tensile strength of the bulk $Mg_{70}Ca_{20}Al_{10}$ alloy is shown in Fig.7, in comparison with those for the Mg-Cu-Y alloy as well as for commercial light weight alloys .The Mg-Ca-Al alloy has a high value of 3.3 x 10^5 Nm/kg which is just the same as that for the Mg-Cu-Y alloy, because of the lower density for the present alloy.

Finally, it is important to describe that the present bulk Mg-Ca-Al alloy has good corrosion resistance which is superior to that for the commercial AZ91-T6 alloy, as shown for the corrosion rate in 3%NaCl solution at 300 K in Fig.8.
Especially, the achievement of the extremely high tensile strength of extruded bulk $Mg_{87.5}Cu_5Y_{7.5}$ and $Mg_{70}Ca_{20}Al_{10}$ alloys are presumably because of the formation of the nanoscale mixed structure consisting of ultra fine grain, homogeneously distributed fine intermetallic compound particulates, which cannot be obtained by conventional thermo-mechanical treatments. It is therefore concluded that the $Mg_{87.5}Cu_5Y_{7.5}$ and $Mg_{70}Ca_{10}Al_{20}$ alloy produced by extrusion of atomized nonequilibrium phase powders at temperatures above T_x has high specific tensile strength which have not been obtained for any Mg-based alloys in practical use. The simultaneous achievement of the good properties allows us to expect that the newly developed Mg-Cu-Y and Mg-Ca-Al alloy is used in some fields which requires simultaneously the high specific strength, high stiffness and high corrosion resistance.

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