Production and Comparison of Adapted Load-Sensitive Magnesium Alloys

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Summary: Magnetic magnesium alloys can be utilised as a load sensitive material, in which the inverse magnetostrictive effect is used in order to measure the actual loads in structural components manufactured from such lightweight sensor alloys. To achieve a material which exhibits magnetic properties, magnesium is alloyed with ferromagnetic materials like cobalt or samarium-cobalt. In order to improve the mechanical properties of these alloys, alloying elements commonly used with Mg must be utilised, which however may have a slight negative impact on the magnetic sensitivity. In this work, two separate magnetic Mg alloys are compared, each with properties matched to the opposing requirements: (a) high load sensitivity and (b) satisfactory mechanical properties, respectively. The precipitation behaviour of the ferromagnetic constituent cobalt in magnesium is briefly shown on the basis of SEM images of a binary Mg-Co alloy. Cyclic loading tests employing harmonic analyses of eddy current signals are utilised in order to verify the alloys' sensory properties. The mechanical properties are investigated using tensile tests.

Keywords: Casting, Magnesium, Microstructure, Monitoring.

1. Introduction

A strict allegiance to lightweight design principles requires the use of lightweight materials, among which magnesium alloys are outstanding because of their high specific strength. However, if overdimensioning of machine or automotive components is to be avoided, the increased loads may make it necessary to monitor forces and stresses that are applied to the structural components. If the component has inherent magnetic properties it can serve as a load sensor itself, because in this case relevant information on the operating conditions can be collected with the magnet material. In order to determine the instantaneous loads which have an effect on the component, the Villari-Effect (inverse magnetostriction) is utilised, which describes the change of susceptibility of a ferromagnetic material underlying mechanical stress [1]. The change in the magnetic state as a result of the deformation of a material's crystal lattice enables the use as magneto-elastic sensors [2-4].

Magnesium however does not have magnetic properties. Thus magnesium alloys containing intermetallic phases which exhibit magnetic properties were developed by the authors and published in previous works [5-7]. These alloys contained the ferromagnetic compound samarium-cobalt as well as low concentrations of standard alloying elements in order to achieve usable magnetic and satisfactory mechanical properties. A detailed description of the employed measuring technology, the harmonic analysis of eddy current signals, is given in [7, 8]. For the characterisation of a material's magnetic properties, the 3rd harmonic is of great significance and therefore used in this work.

In the present article, microstructure and magnetic properties of a binary magnesium-cobalt alloy are investigated. The aim of this study is to determine the influence of the pure ferromagnetic constituent Co apart from further alloying elements used in the previous works by producing a Mg-Co alloy with elevated load sensitivity by casting. Magnetic properties and strength of this alloy are compared to a magnetic Mg alloy with improved mechanical properties based on Mg, Zn and commercial SmCo.

2. Experimental

For the binary magnesium-cobalt alloy, technically pure magnesium was alloyed with a 10 wt.% fraction of pure cobalt powder (purity 99.9%, particle size < 150 µm; Sigma Aldrich Chemie GmbH). The alloy for comparison was based on the commercial ZEK100 (Zn 1 wt.%, RE < 0.5 wt.%, Zr < 0.5 wt.%) alloyed with a 8 wt.% fraction of commercially available samarium-cobalt powder (particle size < 300 µm; Max Baermann GmbH), which was used in [4]. The alloys were manufactured by means of a die casting method using a resistance-heated furnace in a shielding-gas atmosphere (N_2 + 0.3% SF_6) and by employing a boron nitride coated, unalloyed steel crucible. The basic material was melted and held at a temperature of 710°C. At the beginning of the stirring process (80 min at 300 min^{-1}) the magnetic powder was dispensed into the melt. The melt was cast into boron nitride coated cylindrical steel moulds (diameter 50 mm x length 140 mm) which had been preheated to 350°C.

Threaded cylindrical tensile specimens with a nominal diameter of 6 mm were manufactured from the castings as test pieces for both the loading measurements using the Villari-Effect as well as the determination of the mechanical strength values. The SEM analysis of the binary Mg-Co alloy was performed on ground sections of the castings which were polished to 1 µm.

3. Results

In order to investigate the dissolution of the ferromagnetic alloying element cobalt in magnesium and its impact on the magnetic properties the specimens produced in this study were investigated by means of scanning electron microscopy. Subsequently, the magnetic properties of tensile specimens manufactured from the binary Mg-Co alloy were evaluated utilising harmonic analysis of eddy-current signals and compared to the alloy based on ZEK100 and samarium-cobalt.

1.1. Microstructure examination of the Mg-Co alloy

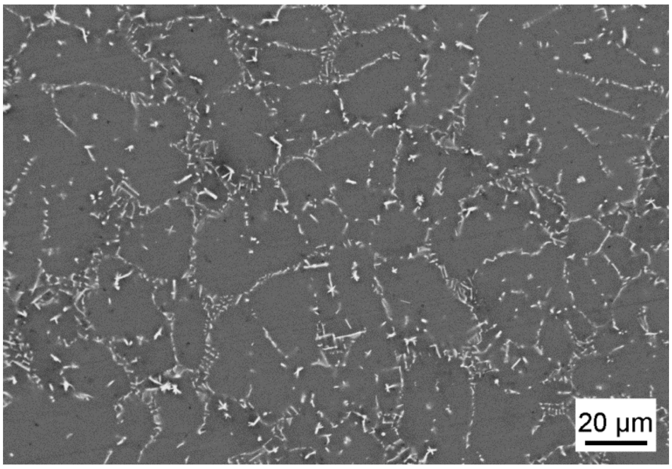

Figure 1. SEM image (RBSD mode) of the microstructure of the binary Mg-Co alloy.

A representative section of the binary Mg-Co alloy's microstructure, as recorded using the compositional contrast mode of the SEM, is depicted in Figure 1. The microstructure is comprised of primary magnesium crystals surrounded by a widespread network of precipitations which, according to measurements by means of energy-dispersive x-ray spectroscopy (EDX), consist mainly of Co (Table 1). These phases exhibit a refined lamellar eutectic structure and seem to enclose the primary Mg crystals.

An EDX area measurement was performed by defining a rectangular ROI with a surface area of $1.3 \cdot 10^{-3}$ mm² including both portions of primary magnesium and the Co precipitations.

Table 1. EDX analysis of the microstructure components.

	Element concentration [wt.%]		
	Mg	Mn	Co
Primary magnesium	99,04	-	0,96
Precipitations	39,47	0,52	60,01
Area measurement	93,08	-	6,92

1.2. Comparison of the magnetic properties of the binary Mg-Co alloy and the alloy ZEK100 + SmCo

Cyclic loading tests employing stepwise increasing loads between 200 and 1400 N were performed in order to determine the alloys' suitabilities as inherent load sensor materials. The material's magnetic properties subject to the cyclic loading were determined with the aid of a harmonic analysis of eddy current signals. After each step the specimens were relieved of the load. As the test results of the two different alloys show (Figure 2), a linear dependency with high reproducibility exists between the amplitudes of the 3rd harmonic and the applied loads. Moreover, the measured amplitudes drop back to a value close to the initial state on unloading the test pieces. Note that the scaling of the vertical axes differs in order to make the changes of the values more visible. Especially for the Mg-Co alloy, a slight hysteresis appears at high loading which is discussed in chapter 4. The values are also depending on the alloy composition. The measured values of the alloy ZEK100 + SmCo are approximately 50% smaller than those of the binary Mg-Co alloy. Furthermore, the two alloys' amplitudes show different ranges between the initial, unloaded state and the highest load (1400 N). For ZEK100 + SmCo a change of the values of $\Delta_{ZEK100+SmCo}$ = 0,44 mV is observed, whereas for Mg-Co the difference is Δ_{Mg-Co} = 0,84 mV. The sensitivity of the alloy based on the pure components Mg and Co is therefore higher.

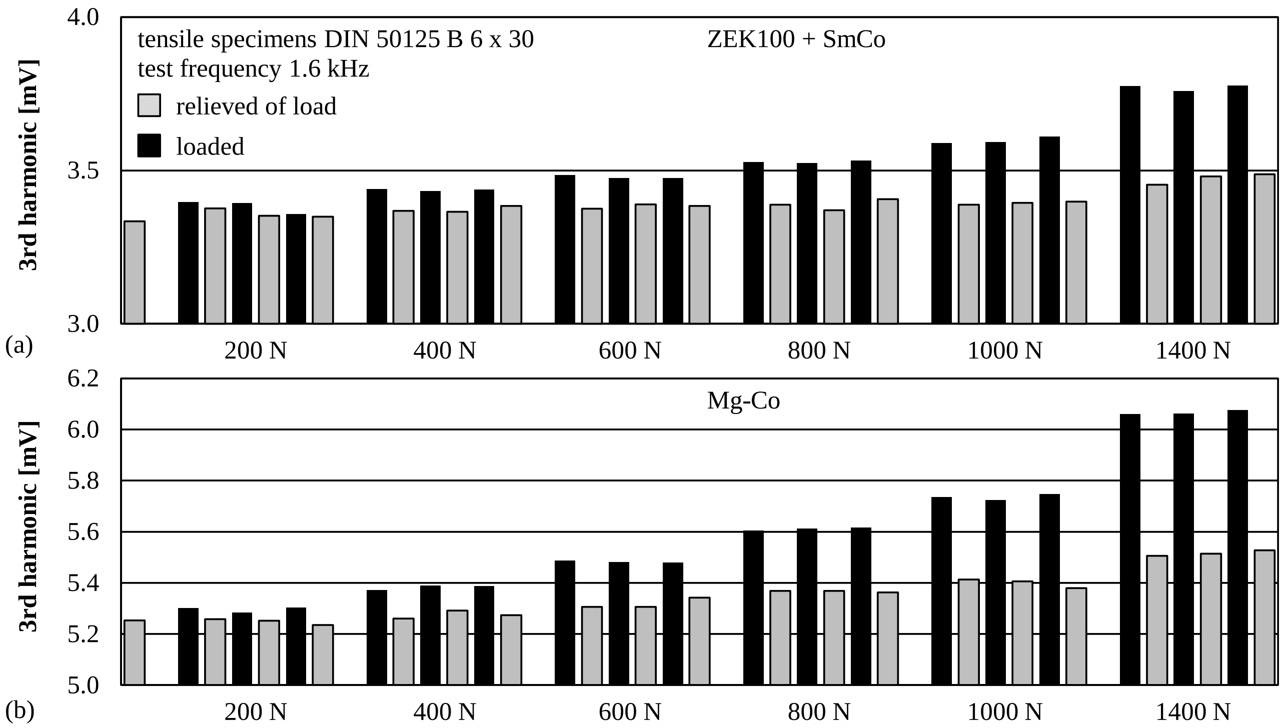

Figure 2. Measured amplitudes of the 3rd harmonic depending on the applied load; alloy ZEK100 + SmCo (a), alloy Mg-Co (b).

1.3. Mechanical properties of magnetic Mg alloys

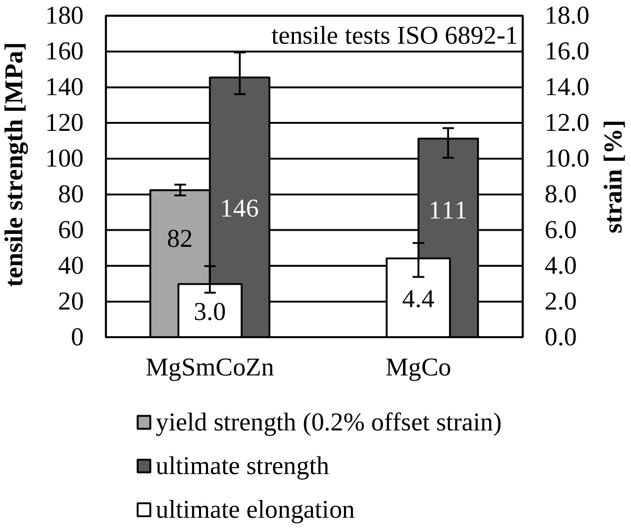

Figure 3. Mechanical properties of the alloy ZEK100 + Sm and the binary Mg-Co alloy in as-cast condition (n = 6).

The mechanical properties of the magnetic magnesium alloys in the as-cast state are presented in Figure 3. Cobalt as an alloying element causes a very slight increase of the ultimate tensile strength compared to literature values of pure Mg (100 MPa [9]) in cast condition. Only ultimate tensile strength and elongation are given for the binary Mg-Co alloy because the exact yield point could not been determined properly due to the shape of the tensile curve. In contrast, the alloy based on ZEK100 and SmCo reaches considerably higher strength values at a lower elongation.

4. Discussion

According to literature [10], a eutectic point exists in the Mg-Co-system which occurs at a Co concentration of 1.91 at.% (4.5 wt.%) and is accompanied by a melting point reduction to a temperature of 635°C. This corresponds with the investigations made in this study. Concluding from the lamellar appearance of the cobalt containing precipitations, the binary Mg-Co alloy consists partly of a eutectic microstructure (Fig. 1). The existence of such a eutectic phase in the castings suggests that the cobalt powder dissolved in the Mg melt.

Although both of the tested alloys exhibit magnetic properties which are suitable for the measurement of instantaneous loads, the results of the cyclic loading tests show that the binary Mg-Co alloy has higher magnetic sensitivity. The hysteresis effects of the 3^{rd} harmonic that could be observed after relieving the tensile specimens of the higher loads (Fig. 2) are probably due to a local exceeding of the yield strength followed by plastic deformation. Unfortunately the yield point of the binary MgCo alloy could not be determined exactly in the tensile tests, because the transition from elastic to plastic deformation was very steady (Fig. 3).

5. Conclusions

In the present study, the production of load-sensitive magnesium alloys with adapted properties was demonstrated. A highly sensitive alloy based on pure Mg and pure Co was produced by die casting and investigated by means of analyses with scanning electron microscopy. The SEM images show primary Mg crystals and a eutectic Mg-Co microstructure.

Magnetic and mechanical properties were compared to an alloy based on the Mg alloy ZEK100 modified with commercial SmCo powder. While the strength of the alloy ZEK100 + SmCo reaches significantly higher values, the amplitudes of the 3^{rd} harmonic of the eddy-current measurements and therefore the sensitivity for the load tests were lower than the comparative values of the binary Mg-Co alloy.

In order to demonstrate the alloys' functioning, a load-sensitive stub-axle of a Formula Student race car has been produced [7]. Other applications for magnetic Mg alloys may include ultra-light load sensor elements for measurement technology.

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