The study of microstructure and mechanical properties of twin-roll cast AZ31 magnesium alloy after constrained groove pressing

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Abstract. Microstructure investigation and microhardness mapping were done on the material with ultra-fine grained structure prepared by constrained groove pressing of twin-roll cast AZ31 magnesium strips. The microstructure observations showed significant drop of the grain size from 200 µm to 20 µm after constrained groove pressing. Moreover, the heterogeneities in the microhardness along the cross-section observed in the as-cast strip were replaced by the bands of different microhardness in the constrained groove pressed material. It is shown that the constrained groove pressing technique is a good tool for the grain refinement of magnesium alloys.

1. Introduction

The need for structural materials with low density and high specific strength, such as aluminium and magnesium alloys, has prompted the development of new casting and forming techniques. In recent years the considerable interest has been devoted to materials processed using severe plastic deformation (SPD) [1-3]. Nowadays, a variety of SPD techniques such as equal-channel angular pressing (ECAP), high-pressure torsion (HPT) and constrained groove pressing (CGP) is used. During the SPD very large strain is imposed into the material. This leads to the rearrangement of dislocations and formation of the ultra-fine grained (UFG) structure. UFG materials are characterized by the submicrometer or even less than 100 nm sized [4] grains and exhibit unique mechanical properties. Since aluminium and magnesium have a large number of applications in automotive and computer industries [5,6], the study of their mechanical properties and formability is very important. Because of the hexagonal close-packed (HCP) structure, magnesium alloys exhibit a tension/compression anisotropy of the mechanical properties and their ductility is limited at ambient temperature. However, it was shown [7, 8] that the ductility of different magnesium alloys can be significantly improved after SPD, even at room temperature. The majority of investigations [9-13] was dedicated to the influence of ECAP and HPT on the microstructure and mechanical behavior of magnesium alloys. Among the main parameters of SPD influencing the structure of the final material are the number of cycles, deformation rate and processing temperature. Figueiredo et al. [9] showed that for the AZ31 magnesium alloy six ECAP passes are necessary to reach the homogeneous grain structure, while after two passes the deformation structure remains still heterogeneous. The grain size and texture are also the significant characteristics which can influence the hardenning of the material. It was shown by Del Valle et al. [8], that the twinning plays minor role in the work hardening of ECAPed alloys compared to the parameters listed above. It was also found, that the major mechanism of strengthening in ECAPed magnesium alloys is grain boundary strengthening [10]. The processing temperature and its influence on the strength of AZ31 magnesium alloy after HPT was considered by Huang et al. [13]. CGP is widely used in industries to compensate the high strength metal plates components used in automobiles. One of the main benefits of the CGP
technique is the improvement of the mechanical properties without any dimensional changes of the material. Nowadays, the majority of publications about the CGP deal with aluminium and its alloys [14, 15]. The information on CGPed magnesium alloys is limited. For instance Ratna Sunil et al. [16] studied the wettability and corrosion resistance of groove pressed (GP) AZ31 magnesium alloy and showed the prospects in its application as implants instead of expensive titanium.

Continuous casting techniques, such as twin-roll casting (TRC), are becoming more popular due to the presence of the much higher solid solution supersaturation and uniform grain size distribution [17]. Both, CGP and TRC techniques are well established on aluminium alloys. No information is available on CGP magnesium materials prepared by TRC technique.

In the present study the TRC AZ31 magnesium alloy was used as a semi-product for further mechanical treatment by CGP. The investigation of the homogeneity along the material cross-section was done by the mapping of the microhardness. The microstructure observations were done using light microscopy.

2. Experimental procedure

The study of the microstructure and microhardness was performed on the AZ31 magnesium alloys with the chemical composition showed in the Table 1. The alloy was cast using TRC technique. During TRC the 650 °C melt of the AZ31 goes through the nozzle between two water-cooled rotating rolls. Solidified strips of the 5,6 mm thickness strip were prepared at the processing speed 1.8 m/min.

|       | Al  | Zn  | Mn  | Ca  | Cu  | Fe  | Mg  |
|-------|-----|-----|-----|-----|-----|-----|-----|
|       | 3.45| 0.98| 0.28| 0.002| 0.002| 0.004| Balance |

*Table 1. Chemical composition of AZ31 magnesium alloy.*

The scheme of the CGP process is given in Fig. 1. The TRC AZ31 magnesium strip was used as an input material. Plates of the 70 x 50 x 5,6 mm were cut from the TRC strip with the longer part parallel to the rolling direction (RD). The CGP process consists of four steps. In the first step (Fig. 1a, b) of groove pressing, a specimen is placed in the die with slight gap which is equal to the sheet thickness. In the second stage (Fig. 1c), flat pressing occurred. After that the specimen is rotated 180° around the pressing direction and the groove pressing stage is repeated (Fig. 1d, e). At the end, the specimen is flattened again (Fig. 1f) [18]. The specimen

*Figure 1. The scheme of the CGP process: a, b, d, e) groove pressing, c, f) flat pressing.*
was heated to 450°C for 10 min before each step. The maximum pressing load was 60 tons.
Standard metallographic techniques were used for the sample preparation and microstructure observations. The microstructure images were taken using Olympus GX51 light microscope and NIS-Elements AR 3.0 software. The microhardness mapping using a QNess Q10A+ machine was done on the same specimens. The Vickers method with a 100 g load was used in order to obtain the microhardness maps. The indentation nets for TRC and CGPed samples included about 600 and 1200 indents, respectively, with the 200 µm distance between them.

Figure 2. Microstructure images of the as-cast TRC AZ31 magnesium alloy: a) cross-section of the strip, b) central part of the strip, c) bulk of the sample made by light microscopy. Frames in the figure (a) indicate the areas where the micrographs (b) and (c) were taken.

3. Results and Discussion

3.1. Microstructure

Figure 2a shows the cross-section of the as-cast sample in the TD. The material exhibits inhomogeneous structure along the cross-section with pronounced columnar structure. In accordance with previous observations [17] deformed areas near strip surface and segregation band related to the impurities and excess of the alloying elements in the central part (Fig. 2b) were observed. In the bulk of the sample the larger columnar grains are tilted towards the RD. The size of those grains achieves 200 µm. Smaller grains in the middle of the strip and near the surface have a size of about 40 µm (Fig. 2b). The region with columnar grains (Fig. 2c) is characterized by numerous dendrites formed due to the non-equilibrium cooling conditions during casting [19]. The AZ31 magnesium alloys mainly consist of two phases: α-Mg matrix and β-Al12Mg17 phase [20, 21]. Previous observations [22] have shown that the β-Al12Mg17 phase particles appear in the as-cast TRC AZ31 magnesium alloy mostly inside the grains of the α-Mg matrix and their volume fraction is homogeneous throughout the entire volume of the material. It was also found [23] that in aluminium-containing magnesium alloys Al12Mg17, as well as α-Mg, phases are located in the interdendritic regions. Because the TRC material exhibits rather inhomogeneous complex
structure containing also large elongated grains, the refinement of the structure by CGP technique was made.

**Figure 3.** Vickers microhardness mapping (HV0.1) of the AZ31 magnesium alloy after TRC.

**Figure 4.** Microstructure images of the TRC AZ31 magnesium alloy after CGP in TD: a) zone of the highest deformation, b) transition zone, c) slightly partially recrystallized deformed area made by light microscopy.
Figure 3 shows the microstructure of the deformed strip. Such a mechanical treatment consisting of only one complete CGP cycle leads to the structure which exhibits heterogeneity along the RD. Regions with different grain size were observed. The grain size is reduced down to 20 µm in the regions of the highest deformation (Fig. 3a). The transition region (Fig. 3b) with the grain size of about 40 µm and weakly deformed area between the grooves where complete recrystallization has not yet occurred are shown in Fig. 3c. Pre-heating at 450 °C for 10 min before each step of the CGP process dissolved the β-particles and, thus, no secondary phases inside the grains were observed.

3.2. Microhardness

The investigation of the microhardness along the cross-section of the TRC and CGPed samples showed significant differences in the hardness. The heterogeneous distribution of the hardness is observed in both materials. Figures 4 and 5a show the microhardness maps of the as-cast material and the material after CGP, respectively. Each color denotes the hardness value, which is indicated on the color key on the right side of the plot. The TRC alloy exhibits inhomogeneity along the ND, while for the CGPed material microhardness values along the ND remain more or less constant. Nevertheless, as can be seen in Fig. 5a, significant differences in microhardness were observed along the RD. In the TRC strip, regions with higher microhardness are related to the higher deformation imposed during the casting process in the central and surface layers where the Vickers microhardness reaches 68 MPa, while the rest of the material is by 20 MPa softer. The differences in the grain size of the TRC material after the CGP affect the microhardness. Fig. 5b shows the cross-section image made by optical microscope in the same scale as the microhardness map. Harder bands in the CGPed material are related to the regions with the smallest grain size (compare Fig. 3a and 3b as is indicated by frames on Fig. 5b). In general, the microhardness of the whole material increases after CGP and achieves the maximum value 96 MPa, which is about 30 % more than for the as-cast TRC alloy. Moreover, this value is more than 45 % higher than the value generally reported for the conventionally as-cast AZ31 magnesium alloy [22, 24].

4. Summary

The AZ31 TRC alloy was used as a basis for the preparation of the fine grained material with improved local mechanical properties. After one cycle of the CGP significant microstructure changes were observed. The reduction of the grain size from 200 µm down to 20 µm in the regions of the highest deformation was detected. Grain refinement was followed by the improvement of the microhardness. As far as there is almost no reduction in the thickness of the sample (less than 10%), the CGP appears to be a suitable tool for the grain refinement of TRC magnesium strips. It is expected that the inhomogeneity in microstructure and microhardness along the cross-section of the studied specimens could be eliminated after more CGP cycles.
Figure 5. Vickers microhardness mapping (HV0.1) (a) of the TRC AZ31 magnesium alloy after CGP and the cross-section image from light microscope (b).

Acknowledgements
Authors are grateful for the financial support of the Czech Science Foundation under the project P107-12-0921 and to the grant SVV-2014-269303.

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