Change of the casting magnesium alloys structure during the melt solidification on rotating heat receiver

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Abstract. Using the methods of metallography, measurements of mechanical properties and X-ray analysis, we investigated the effect of rapid quenching by the method of extracting a hanging melt drop for casting alloys belonging to the Mg-Al-Zn (ML-5) and Mg-Nd-Zr (ML-10) systems. It is shown that the strength of the fibers significantly exceeds the ones values inherent for these materials, especially for the alloy ML-10, what is associated with the presence of a favorable preferential orientation of the rapidly crystallized fibers after rapid crystallization.

1. Introduction
Magnesium and its alloys play an increasingly important role in aerospace engineering due to their high specific strength and rigidity. Analysis of the current state of research shows that the strength and ductility of magnesium alloys can be enhanced by applying high-rapid melt solidification technologies, which allows to obtain a fine and more uniform micro- and nanocrystalline microstructure and thereby improve the service properties of magnesium and its alloys [1–5].

The present work is dedicated to investigation of the effect of rapid quenching by the method of extracting a hanging melt drop (EHMD) for casting alloys of the Mg-Al-Zn (ML-5) and Mg-Nd-Zr (ML-10) systems. The main advantage of the EHMD method in comparing with other foundry methods for producing fibers is the using of non-crucible melting, which makes it possible to obtain fibers from chemically active and refractory metals [6].

2. Materials and research methods
In the work the alloys of ML-5 and ML-10 in the form of rods with a diameter of 12 mm and a length of 200 mm were used. Cast billets had the following chemical composition. Alloy ML-5: Al – 8.2%; Zn – 0.6%; Mn – 0.2%. Alloy ML-10: Nd – 2.5%; Zr – 0.6%; Zn – 0.5%. To obtain discrete particles by the method EHMD the self-made installation EVCR-6 RN (figure 1(a)) was used. When using the EHMD method, the lower end of a vertically located rod was melted to form a hanging melt drop, which solidifies on contact with a rotating cooled heat exchanger. By varying such process parameters as the rotation rate of the heat exchanger, the melt feed rate and heating power, fibers with a diameter in range of 30–80 μm and the width 90–150 μm can be obtained. High cooling rates about 10⁷ K/s was achieved during solidification process. Preparation of dispersed particles carried out in argon at a pressure of ~80 kPa. The fibers in the cross section have a sickle shape (figure 1(b)).
strength of the fibers was measured on the Instron 5982 breaking machine. The tested fibers were fixed on a specially prepared frame, the loading rate was 1 mm/min. The damage area was measured using VEGA 3 SBH scanning electron microscope.

![Installation EVKR-6 PH (a) and the type of fiber (b).](image)

**Figure 1.** Installation EVKR-6 PH (a) and the type of fiber (b).

### 3. Results of research and discussion

The structure of the ML-5 alloy in the initial cast state is shown in figure 2(a) and contains Mg-Al solid solution and the particles of γ-phase (Mg$_{17}$Al$_{12}$). According to the results of X-ray analysis using the measurement of the lattice distances and the known dependences of the lattice distances for the Mg-Al solid solution on the aluminum content, its amount was estimated at 5.5 at. %. The lattice distances of the solid solution had the following values: $a = 0.3187$ nm, $c = 0.5182$ nm, $c/a = 1.626$. The γ-phase microhardness was HV240 and microhardness of solid solution was HV74. Clear X-ray reflections of γ-phase are visible on the X-ray picture.

![Microstructure of the ML-5 alloy in the cast state (a) and after quenching (b).](image)

**Figure 2.** Microstructure of the ML-5 alloy in the cast state (a) and after quenching (b).

The structure of the alloy after rapid quenching is shown in figure 2(b) and is represented by a supersaturated solid solution, the lattice distance of the solid solution had the following values: $a = 0.3177$ nm, $c = 0.5164$ nm, $c/a = 1.625$. The aluminum content in the solid solution calculated from these values of the lattice distances was 8.4 %, that is almost 3 % more than the aluminum content in the solid solution in the cast alloy. Significant supersaturation of the solid solution with
aluminum explains an absence of the $\gamma$-phase reflections on the X-ray picture and the corresponding reduced microhardness to HV64, since the effect of solid solution hardening by aluminum atoms in this case does not compensate for the possible hardening effect of Mg$_{17}$Al$_{12}$ intermetallic particles.

The microstructure of the ML-10 alloy in the cast state is shown in figure 3(a). X-ray analysis showed the presence of a solid solution and distinct reflections of the Mg$_{12}$Nd phase. The lattice parameters of the solid solution of the cast alloy had the following values: $a = 0.3210$ nm, $c = 0.5207$ nm, $c/a = 1.622$. The microhardness of the solid solution was HV65, the microhardness of the grain boundaries was HV87.

![Figure 3. Microstructure of the alloy ML-10 in the cast state (a) and after quenching (b).](image)

The microstructure of the alloy after rapid melt quenching is shown in figure 3(b). The lattice parameters of the solid solution had the following values: $a = 0.3209$ nm, $c = 0.5208$ nm, $c/a = 1.623$. X-ray analysis did not detect the presence of the Mg$_{12}$Nd phase, perhaps that is due to its smaller amount in the alloy and to the greater dispersion of the precipitates. Significant changes in the lattice distances after quenching were not found. The microhardness of the fibers was HV62.

For the fibers of the ML-5 and ML-10 alloys, the mechanical properties were evaluated by tensile testing. The applied technique allowed to calculate some mechanical characteristics of the fiber material, which are listed in table 1. It should be noted that the strength of the fibers significantly exceeds the values obtained on cast materials, in particular for the ML-10 alloy. Analysis of the X-ray studies results have shown that with the testing direction, which coincides with the axial direction of the fibers, the direction of the “c” axis of the HCP magnesium lattice predominantly coincides. It is known that for this direction the Schmid factor for the most easily activated in magnesium and its alloys, the basal slip is zero, and for close to the “c” axis directions has low values, which leads to increased strength in these directions, which, as is known, inversely proportional to the magnitude of the Schmid factor.

![Table 1. Strength and ductility values of the fibers of the alloys ML-5 and ML-10](image)
4. Conclusions
1. For the ML-5 alloy, rapid crystallization leads to increasing the aluminum content in the solid solution from 5.5 % in the cast state to 8.4 % after quenching, that explains the absence of $\gamma$-phase reflections on the X-ray picture of rapid quenching samples.
2. In the ML-10 alloy in the cast state, in addition to the solid solution, distinct reflections of the $\text{Mg}_{12}\text{Nd}$ phase were observed, after rapid crystallization, no significant changes in the lattice periods occur, and the presence of the $\text{Mg}_{12}\text{Nd}$ phase was not detected.
3. It is shown that the strength of the fibers substantially exceeds this values obtained for cast materials, especially for the ML-10 alloy, that is associated with the presence after rapid crystallization of the preferential orientation of the fiber axes parallel to the directions close to the “c” axis of the HCP magnesium lattice with close to zero Schmid factors values.

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