Application of heat treatment and hot extrusion processes to improve mechanical properties of the AZ91 alloy

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Abstract

The main aim of this paper is to evaluate the effects of hot working (extrusion) and heat treatment on room temperature mechanical properties of magnesium-based AZ91 alloy. The results were compared with as-cast condition. The examined material had been obtained by gravity casting to permanent moulds and subsequently subjected to heat treatment and/or processed by extrusion at 648 K. Microstructural and mechanical properties of properly prepared specimens were studied. \(R_m\), \(R_{p0.2}\) and \(A_s\) were determined from tensile tests. Brinell hardness tests were also conducted. The research has shown that hot working of AZ91 alloy provides high mechanical properties unattainable by cast material subjected to heat treatment. The investigated alloy subjected to hot working and subsequently heat-treated has doubled its strength and considerably improved the elongation - compared with the as-cast material.

Keywords: Magnesium Alloy, Heat Treatment, Hot Working

1. Introduction

Over the past few years (2000÷2006), the world production of magnesium has been reported to enjoy an average annual growth of about 14% [1]. Because of low mechanical properties, pure magnesium has not found any wider application as a structural material. On the other hand, in alloyed form, it is used for casting and plastic working. The most beneficial feature of magnesium alloys is their extremely low density of about 1.8 g/cm³ (it is – as a matter of fact – the lowest density among all the commercial alloys) [2]. It is combined with a supreme specific strength, good machinability and thermal conductivity, easy recycling, good damping capacity and ability to absorb electromagnetic waves [3]. These are the reasons why magnesium alloys are becoming the preferred engineering material in automotive industry, where the reduced weight of elements means less of fuel consumption, and hence lower rate of the greenhouse gas emissions. The majority of intricate parts made from magnesium alloys are fabricated by various casting processes, like gravity casting into metal and sand moulds, pressure die casting, squeeze casting, or semi-solid (thixocasting) process [4]. The reason that lies behind this fact is rather poor plastic deformability at room temperature of magnesium and its alloys, which considerably limits the applicability of cold working processes.

Magnesium crystallizes in the hexagonal system; the ratio of an elementary cell parameters \(c/a\) is 1.624, which means that packing of atoms in the lattice is close to an ideal condition. The deformation at room temperature is very limited; almost only along the planes of the hexagon base (0001)<1120>. In this
situation, only three slip systems are available, which is not sufficient for a metal to be considered plastic since it should have at least five independent slip systems [5]. This is the reason why magnesium alloys are suitable for plastic working only at high temperatures, when the slip along the side (prismatic) and internal (pyramidal) planes becomes possible, making them finally plastic [6].

During high-temperature metal deformation, several phenomena occur at the same time: hardening, dynamic recovery (DRV) and dynamic recrystallisation (DRX). Magnesium alloys are characterised by the low stacking fault energy (60÷78 kJ/mol), and therefore it is the dynamic recrystallisation that plays the leading role in their hot plastic working (above 513 K) [7]. DRX is responsible for an abatement of the deformation effects; it improves ductility and reduces the resistance to flow, thus enabling the deformation process to proceed without the need for continuous increasing of external forces [3].

Because of high aluminium content (~ 9.0 wt.%), AZ91 is considered typical cast alloy [8]. The research described in this paper aims not only at the determination of its mechanical properties after heat treatment or extrusion, and comparing them with as-cast condition, but also at proving that the division into cast alloys and alloys for plastic working is the matter of purely conventional agreement.

2. Methods

The investigations were made on AZ91 magnesium alloy. Its chemical composition is given in Table 1.

Table 1.

<table>
<thead>
<tr>
<th>Chemical composition of the examined alloy [9]</th>
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<tbody>
<tr>
<td><strong>Alloy designation</strong></td>
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<tr>
<td></td>
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<tr>
<td>AZ91</td>
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</table>

The cylindrical specimens of Ø 60 mm dia. were cast in permanent moulds and machined to a final diameter of Ø 40 mm. The specimens of the required dimensions were subjected to the process of hot direct extrusion carried out at the Department of Non-Ferrous Metals, University of Science and Technology in Cracow.

The following process parameters were observed: elongation factor - 16, temperature – 648 K, and ram feed rate – 0.5 mm/s. Thus produced wire of Ø 10 mm dia. was cut into 110 mm x 10 mm specimens for mechanical tests (reference line – 50 mm), and into the specimens for hardness measurements and microstructural examinations. Half of the specimens were subjected to a heat treatment, i.e. ageing at 343 K for 16 hours under the argon protective atmosphere (condition: T5).

The values of the mechanical properties of AZ91 alloy in the starting condition and after heat treatment (conditions: T4, T5, T6) were taken from earlier studies on this subject [9, 10]. The heat treatment was conducted according to Standard Practice for Heat Treatment of Magnesium Alloys [11]. The solutioning to condition T4 was carried out at a temperature of 689 K for 16 h; the parameters of alloy ageing to condition T5 were as follows: temperature – 343 K, time – 16 h. The material after solutioning was aged to the precipitation hardened state (T4 to T6) at a temperature of 343 K for 16 h. The heat treatment process was carried out under the argon protective atmosphere.

Static tensile tests at room temperature were conducted on an INSTRON 1115 machine according to PN-EN 10002-1:2004 at a rate of 0.6 mm/min. Four specimens were tested in each test variant. Hardness was measured by Brinell method using a 2.5 mm diameter indenter and a load of 625 N according to PN-EN ISO 6506-1:2002. In each test variant six measurements were taken on the specimen cross-sections.

Microstructure was examined under an OLYMPUS DP70 optical microscope at the Institute of Light Metals in Skawina. The examinations were preceded by standard grinding and polishing of specimens, which were next etched in nital (3% solution of nitric acid in ethyl alcohol). Percent fraction of the Mg17Al12 phase precipitates was calculated by a grid method according to PN-84/H-04507/01.

3. The results and discussion microstructural examinations

Representative microstructures present in the three variants of AZ91 alloy are shown in Figure 1 in function of the processing technique. The structure typical of the starting (as-cast) condition, i.e. the 0 structure, is shown in Figure 1a. Its composition includes the solid solution of αMg (light colour) and large, dark-coloured, precipitates of an intermetallic equilibrium Mg17Al12 phase – present mainly on grain boundaries.

The microstructures of alloy subjected to plastic working, i.e. to hot extrusion (PP), are shown in Figures 1b and 1c. The structure of PP specimens differs quite considerably respective of the starting condition. At the same magnification, the results of very severe plastic deformation suffered by the examined alloy are very well visible. The precipitates of Mg17Al12 phase in specimens subjected to plastic working are finer and characterised by much higher degree of dispersion. The microphotograph in Figure 1b does not allow the grain size to be exactly determined, but knowing that the Mg17Al12 phase is mainly present on grain boundaries one can assume that the size of the grains has decreased quite considerably.
Figures 1d and 1e show microstructures observed in specimens of AZ91 alloy extruded and then subjected to heat treatment (PPS) at a temperature of 343 K for 16 h. Compared with microstructures of alloy hot worked but without heat treatment, the morphology of Mg17Al12 phase precipitates has changed. The percent fraction of this phase in the structure has increased from 22.7% (PP) to 47.6% (PPS) with the precipitates undergoing partial coagulation. This indicates a significant degree of supersaturation of the αMg solid solution with an alloying element during alloy cooling after extrusion. The images of microstructures observed in PP and PPS specimens on their longitudinal sections (Figs. 1c and 1e) show, typical of the extruded material, considerable grain elongation in the direction of extrusion, caused by severe plastic deformation to which the examined alloy has been subjected.

Fig. 1. Microstructures of AZ91 alloy; a) as-cast condition, mag. 200x; b) hot-worked, cross-section, mag. 200x; c) hot-worked, longitudinal section, mag. 50x; d) hot-worked and heat-treated, cross-section, mag. 200x; e) hot-worked and heat-treated, longitudinal section, mag. 50x
4. Testing of mechanical properties

The results of the tests are given in Table 2, while Figure 2 depicts them in a graphic form. Table 3 shows percent changes in the properties of the examined alloy respective of its as-cast condition and in function of the processing treatment type.

From Figure 2 it follows that the examined alloy in as-cast condition can offer rather poor mechanical and plastic properties. This is directly related with its coarse-grain structure described above. Its tensile strength at a level of 167 MPa and the yield point $R_{p0.2}$ reaching 81 MPa are indeed the values much too low to make AZ91 useful in as-cast condition for structural applications, especially if taking into consideration the fact that the very popular and cost effective alloys from an Al-Si system are in most cases capable of offering much better properties.

Table 2.
Mean values of the mechanical properties of AZ91 alloy and their standard deviations [9]

<table>
<thead>
<tr>
<th>Sample designation</th>
<th>Alloy condition</th>
<th>$R_m$ [MPa]</th>
<th>$\sigma^*$</th>
<th>$R_{p0.2}$ [MPa]</th>
<th>$\sigma^*$</th>
<th>$A_0$ [%]</th>
<th>$\sigma^*$</th>
<th>HB [HB]</th>
<th>$\sigma^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>As-cast (F)</td>
<td>167</td>
<td>20</td>
<td>81</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>67</td>
<td>2</td>
</tr>
<tr>
<td>T4</td>
<td>Solution heat treated</td>
<td>197</td>
<td>35</td>
<td>81</td>
<td>11</td>
<td>9</td>
<td>4</td>
<td>68</td>
<td>3</td>
</tr>
<tr>
<td>T5</td>
<td>Aged (without previous solutioning)</td>
<td>180</td>
<td>12</td>
<td>95</td>
<td>5</td>
<td>2</td>
<td>1</td>
<td>71</td>
<td>5</td>
</tr>
<tr>
<td>T6</td>
<td>Solution heat treated and artificially aged</td>
<td>241</td>
<td>31</td>
<td>106</td>
<td>16</td>
<td>5</td>
<td>1</td>
<td>78</td>
<td>9</td>
</tr>
<tr>
<td>PP</td>
<td>Hot-worked</td>
<td>312</td>
<td>12</td>
<td>183</td>
<td>8</td>
<td>13</td>
<td>4</td>
<td>90</td>
<td>3</td>
</tr>
<tr>
<td>PPS – T5</td>
<td>Hot-worked and aged</td>
<td>322</td>
<td>5</td>
<td>206</td>
<td>10</td>
<td>11</td>
<td>2</td>
<td>91</td>
<td>5</td>
</tr>
</tbody>
</table>

*standard deviation

Fig. 2. Graphic representation of relationships between mechanical properties and conditions of AZ91 alloy [9]
A maximum heat-treated strength offers the alloy after solutioning and artificial ageing to condition T6. Increasing further the strength of gravity cast AZ91 alloy through heat treatment is very difficult. Having $R_m$ at a level of up to 300 MPa is feasible only through properly applied plastic (thermo-plastic) working.

The examined alloy extruded at a temperature of 648 K (PP) is characterised by very good mechanical properties and excellent ductility. Its ultimate tensile strength is 312 MPa and the yield point $R_{p0.2}$ – 183 MPa, which means percent increase of 87% and 126%, respectively, compared with the as-cast (starting) condition. The elongation on 5-fold specimens has reached the value of 13%, which means a gain of 225%. Taking into account the low density of AZ91 alloy, amounting to about 1,81 g/cm³, this result is very satisfactory. No doubt that this considerable improvement in properties is the result of a combined effect of different factors. First, it means eliminating through hot working the casting defects, adversely affecting the mechanical and plastic properties of the alloy. Next, it means strong grain refinement, which affects the alloy hardening behaviour, especially in hexagonal system [12]. This is due to the fact that in A3 system, at room temperature, the slip is practically possible along one single plane only (0001), which considerably complicates the propagation of deformation (slip engagement) in other grains.

The observed hardening of material is also due to a change in the morphology of Mg$_{17}$Al$_{12}$ phase precipitates, i.e. diminishing of their size and strong dispersion. The next factor contributing to alloy hardening during hot working is the visible elongation of grains, which follows the extrusion process and causes some anisotropy of alloy properties. The more elongated are the grains, the higher are the mechanical properties of the material in direction of the extrusion [13]. However, the elongation of grains brings some adverse effects, too, e.g. strength variations (SDE - Strength Differential Effect) [14]. The material affected by SDE is characterised by lower yield point in compression compared with tension.

Further improvement in mechanical properties of the examined alloy was obtained when the extruded specimens were subjected to a heat treatment comprising artificial ageing. Owing to this treatment, the yield point increased by 13% (compared with PP specimen) and $R_m$ by 3%, unfortunately on the cost of elongation, which dropped slightly. The reason was increased number of the Mg$_{17}$Al$_{12}$ phase precipitates, which coagulated and formed clusters, making both ultimate tensile strength and ductility drop.

Table 3.
Percentage changes in mechanical properties of AZ91 alloy in function of the processing type, referred to as-cast condition

<table>
<thead>
<tr>
<th>Designation of specimens</th>
<th>Alloy condition</th>
<th>Change of [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$R_m$</td>
</tr>
<tr>
<td>0</td>
<td>As-cast (F)</td>
<td>-</td>
</tr>
<tr>
<td>T4</td>
<td>Solution heat treated</td>
<td>+18</td>
</tr>
<tr>
<td>T5</td>
<td>Aged (without previous solutioning)</td>
<td>+8</td>
</tr>
<tr>
<td>T6</td>
<td>Precipitation hardened</td>
<td>+44</td>
</tr>
<tr>
<td>PP</td>
<td>Hot worked</td>
<td>+87</td>
</tr>
<tr>
<td>PPS – T5</td>
<td>Hot worked and aged</td>
<td>+93</td>
</tr>
</tbody>
</table>

5. Conclusions

The results of the investigations described in this study enable the following conclusions to be drawn:

- it is possible to subject the cast AZ91 alloy to plastic working by hot extrusion,
- the application of hot plastic working (extrusion) enables obtaining the mechanical properties (plastic properties, in particular) unattainable for products made from AZ91 alloy when in as-cast condition,
- the heat treatment of AZ91 alloy subjected to plastic working gives but only very modest results (especially as regards the increase of yield point).

Acknowledgements

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References

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