ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 28, No. 3. 2022

Hardness and Conductivity of Die Forged ZYK530 Magnesium Alloy

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crossref http://dx.doi.org/10.5755/j02.ms.28687

Received 23 March 2021; accepted 03 September 2021

The relationship among the microstructure, hardness and electrical conductivity of the as-forged ZYK530 Mg alloy after heat treatment was analyzed and studied using a microscope, X-Ray Diffractometer, eddy current conductivity meter, and Vickers microhardness tester, to explore optimum heat treatment process of ZYK530 Mg alloy. The results show that: with the prolongation of holding time, the electrical conductivity and microhardness show the same change trend, both of which show an oscillatory upward trend, and then decrease in an oscillatory downward trend after reaching the peak value. There is a linear positive correlation between the conductivity and the hardness, and the fitting results of the conductivity and hardness are in good agreement with the measured results; combined with the actual production, when the heat-treatment is 480 ℃ × 8 h + 220 ℃ × 3 h, the highest hardness is 79.2 HV, the electroconductivity is 36.2%IACS, and the comprehensive performance is the best, which is the best heat treatment process.

Keywords: heat treatment, die forged ZYK530 Mg alloy, hardness, conductivity.

1. INTRODUCTION

Mg alloy has the advantages of low density, high specific strength and specific stiffness, good cutting property, good heat dissipation, good electromagnetic shielding type and easy recovery. It is considered as one of the lightweight, miniaturization, high integration and environmental protection requirements of the current products. As “the lightest green gold in the 21st century”, it’s favored by and the majority of material researchers and widely used in the fields of automobile, aerospace,3C and military industry [1–5]. At present, the development of magnesium alloys is mainly focused on magnesium alloys because of their high strength, high toughness, high corrosion, heat resistance, and good plastic deformation [6, 7].

In addition, in the practical high-temperature application of Mg alloy, heat dissipation is one of the key technical problems in the application of magnesium alloy. For example, the current fourth generation of green light source LED lamp has the remarkable characteristics of high efficiency, energy saving, long life, green environmental protection, and its main lighting components such as lamp holder, street lamp shell, downlight shell, bulb lamp shell, tunnel lamp shell and LED heat dissipation module can all be made of magnesium alloy. The heat dissipation problem of magnesium alloy is one of the bottlenecks that affect the development of the LED lighting industry [8, 23]. As we all know, to improve the effective lighting of LED lamps for road lighting, the illuminance of LED lamps must be improved. The premise of improving the illuminance is to increase the power of the products, and increasing the power is bound to increase the heat energy. Therefore, to prevent the occurrence of light decay, the heat generated must be quickly exported, that is to say, the heat dissipation technology determines the service life of LED lamps. Therefore, the core problem of high-power LED lamps is to solve the heat dissipation and control of light decay. In addition to the structural design, the material selection of LED shell and heat dissipation components is the key to solve the problem of LED heat dissipation [8, 23]. Therefore, designing magnesium alloy with good conductivity, good heat resistance and good mechanical properties is the key technology to ensure the service life of high-power LED lamps. The corrosion resistance and thermal conductivity of heat-resistant magnesium alloy determine the ability of magnesium alloy to keep the parts working at a lower temperature during high-temperature service [9].

According to the research, there is a linear relationship between the electrical conductivity and the thermal conductivity of the metal alloy, that is, the conductivity of the alloy measures the level of the thermal conductivity of the alloy [10]. At present, ZK series magnesium alloys have excellent mechanical properties and corrosion resistance in wrought magnesium alloys, so they are one of the most studied Mg alloys [7]. The zinc content of this kind of alloy is poor in heat resistance and has a large warm tendency. Therefore, many researchers add appropriate amounts of rare earths, such as Y, Ce, Nd, Dy, etc., to refine the grains, and form a dispersion-strengthened rare earth phase with Mg, which will improve the findability and creep force of ZK alloy, thereby improving the mechanical properties of the alloy [11]. However, there are few studies on the heat transfer and electrical conductivity of this type of alloy, at the same time, the electrical conductivity is closely related to the stress corrosion resistance of the alloy. Generally, the stress corrosion resistance of alloys increases with the increase of the electro-conductivity, so the electron-

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conductivity is often used as an important index to judge the performance of the alloy. Because the measurement of thermal conductivity and corrosion resistance of the alloy is relatively complex, however, the measurement of electrical conductivity is relatively simple. In this paper, the effects of heat treatment on the microstructure, hardness and electro-conductivity of die forged ZYK530 Mg alloy by heat treatment are studied, which provides some experimental reference for developing new heat-resistant, high-strength and corrosion-resistant wrought magnesium alloys.

2. EXPERIMENTAL METHODS

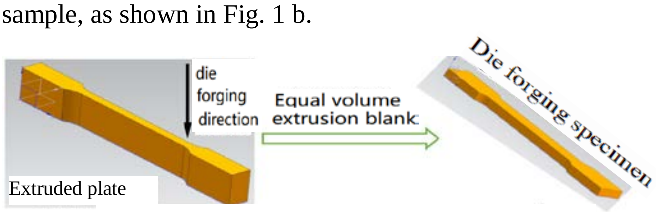
2.1. Experimental materials

Based on ZK60 Mg alloy, a crucible melting process is adopted. The Mg-30 %Y master alloy was added according to the weight of solution at 750 ℃, after rare earth was dissolved, the alloy was refined with Ar gas for 15min, and then cooled to 720℃ for semi-continuous casting. The alloy composition is analyzed by XRF-1800 Fluorescence, as shown in Table 1.

Table 1. Chemical composition of ZYK530 Mg alloy

Alloy	Chemical composition, mass fraction %							
	Zn	Zr	Y	Mn	Fe	Si	Ni	Cu	Mg
ZYK530	4.8918	0.5187	2.8956	0.0063	0.0018	0.0029	0.0009	0.0026	Bal.

Then pre-formed by extrusion on an 800MN extruding machine, the extrusion ratio was 16, the extrusion temperature was 400℃, and the extrusion velocity was 13 ~ 17 mm/s, as shown in Fig. 1 a. The extrusion blank was cut into pieces of 100 mm × 9.0 mm × 2.4 mm by wire cutting, the volume of the die forging blank was the same as that of the tensile sample. After heating the resistance furnace and the self-made die to 400 ℃, the extruded blank was put into the resistance furnace and kept for 12 min, then, the die forging process was carried out on a 2 MN forging press. The die forging process is shown in Fig. 1. The die forging speed was 5 ~ 12 mm/s, and the deformation degree is 50 %, the sample was air cooled, the flash was removed and mechanically polished to obtain the sample, as shown in Fig. 1 b.



a b

Fig. 1. The processing of forming a specimen by die forging

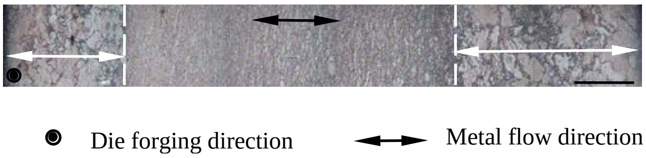
2.2. Experimental methods

The ZYK530 sample after die forging was a solid solution and artificial aging treatment. The solution process was 480 ℃ × 8 h, the artificial aging treatment process was 480 ℃ × 8 h + 200 ℃/220 ℃ and 200 ℃/220 ℃, the aging holding time was 0.5 h, 1.5 h, 3 h, 5 h, 10 h, 15 h, 20 h, 25 h, water cooling, and use wire cutting to take 10 mm × 10 mm × 2.4 mm near the gripping end of the gauge length as corrosion and conductivity test samples, then the HV-1000 Vickers hardness tester was used to test the hardness, and the average value of 5 points was measured for each sample; the eddy conductivity meter (PZ-60A) was used to test the conductivity of the sample, and 5 points were taken as the average value for each sample; after grinding and polishing, the metallographic sample was corroded in a mixture of 1.5 g picric acid + 25 ml ethanol + 5 ml acetic acid + 10 ml distilled water for about 3 ~ 10 s. The microstructure of the alloy was observed by a microscope. The phase and morphology of ZYK530 Mg alloy were analyzed by XRD(DX-2700), SEM(TESCAN-S8000) and EDS. The effect of phase change on hardness and conductivity of ZYK530 Mg alloy was analyzed.

3. EXPERIMENTAL RESULTS AND ANALYSIS

3.1. Microstructure of ZYK530 Mg alloy

When the deformation temperature of the alloy exceeds 1/3 of the melting point of the alloy, obvious dynamic recrystallization will occur during deformation [12]. Fig. 2 shows the low power microstructure of as-forged ZYK530 magnesium alloy. During the die forging process, the sample length of the extruded blank remains unchanged, and the alloy can only flow laterally, the cross-section aspect ratio is 3.5. Due to the uneven die forging stress and easy instability during the die forging process, severe non-uniform recrystallization occurs on both sides of the die cavity wall. The maximum grain size was more than 890 μm and the minimum was less than 1.5 μm, which occupies about 48 % of the entire cross-section, such as Fig. 2 a area "A", with an average hardness of 69.8 HV. At the same time, near the middle of the sample, the specific surface area of the die forging fiber streamline microstructure formed during the die forging deformation process is relatively large, as well as the interface energy, it is difficult to release the deformation heat in a short time during the die forging deformation, which makes the alloy microstructure present equiaxed recrystallized grains, which are distributed perpendicular to the direction of die forging, and the grain size is relatively uniform. The average grain size is about 8.71 μm, which accounts for about 52 % of the entire cross-section, as shown in Fig. 2 a area "B"; its average hardness is 75.3 HV, which is 7.9% higher than the average hardness of area "A"; the microhardness of the untreated sample is 72.6 HV, and its electrical conductivity is 26.5 % IACS. Fig. 2 b is an enlarged view of area "A", which shows that dynamic recrystallization is occurring on the grain boundaries of the alloy; the grain size of the alloy is relatively uniform, and the grains are distributed along the deformation direction, as show the enlarged view of area "B" in Fig. 2 a. Under the action of die forging stress, the grains in the alloy are bent and broken, forming lots of fine grains, and under the action of 3-dimensional forging stress, the grains in the alloy undergo a certain deflection, and the grains rearrangement are achieved, as shown in Fig. 2 c. According to relevant research [13, 23 – 25], the phase composition of Mg-Zn-Y-Zr alloy is related to the Y/Zn atomic ratio.



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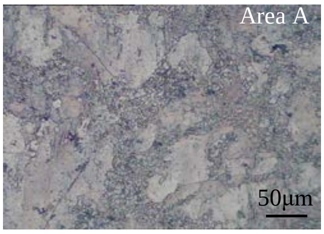
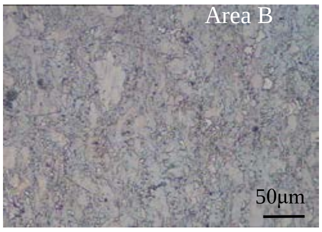
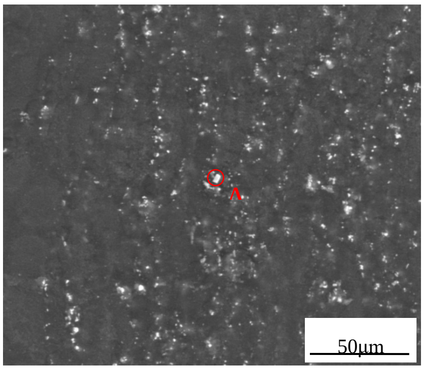




b c

Fig. 2. Microstructure of as-forged ZYK530 Mg alloy



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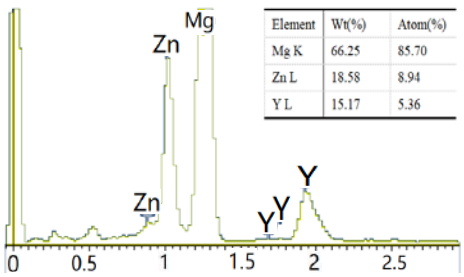


b

Fig. 3. a – SEM image; b, c – EDS spectrum of as-forged ZYK530 Mg alloy

When Y/Zn atomic ratio is 0.16, the alloy mainly consists of the I-Mg_3Zn_6Y phase; when Y/Zn atomic ratio is 0.16 ~ 0.33, the alloy mainly consist of W-$Mg_3Zn_3Y_2$ and I-Mg_3Zn_6Y phase; when Y/Zn atomic ratio is 0.33 ~ 1.32, the alloy mainly consists of the W-$Mg_3Zn_3Y_2$ phase; while when Y/Zn atomic ratio is greater than or equals to 1.32, the alloy mainly consists of the W-$Mg_3Zn_3Y_2$ phase+Z-$Mg_{12}YZn$(LPSO) phase. According to SEM and EDS analysis with Fig. 3, the Y/Zn atomic ratio of as-forged ZYK530 is 0.6, but combined with Fig. 4 XRD, in addition to the α-Mg base, the as-forged ZYK530 magnesium alloy is mainly composed of I-Mg_3Zn_6Y, W-$Mg_3Zn_3Y_2$, Z-$Mg_{12}YZn$ phase, $Mg_{24}Y_5$, a small amount of Mg_2Zn_3, uncertain phase and a small amount of Zr mixed phase. The result is inconsistent with the relevant literature. The reason may be that after the as-cast ZYK530 magnesium alloy was formed by two processes of high temperature extrusion and high temperature die forging, the phases of I phase, W phase, Z phase were transformed at high temperature, due to the short time and the incomplete phase transition, the XRD of the die-forged ZYK530 magnesium alloy detected I phase, W phase, Z phase and a small amount of $Mg_{24}Y_5$, Mg_2Zn_3, as well as uncertain phase and a small amount of Zr mixed phase composition, as shown in Fig. 4, many small peaks can be seen, and these small peaks need to be further determined in the follow-up research.

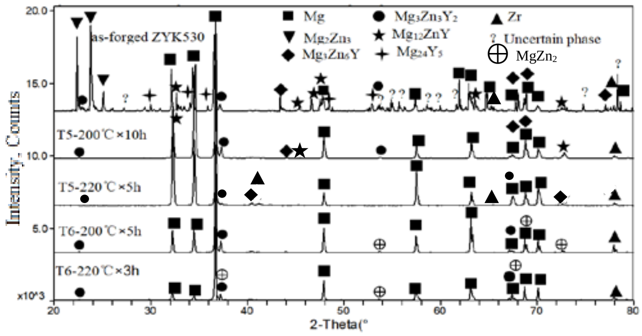
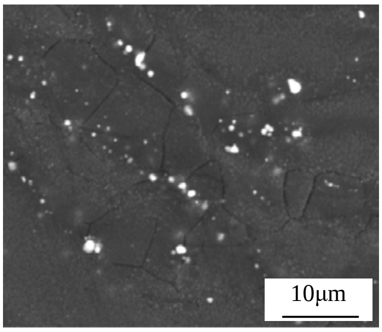


Fig. 4. XRD patterns of as-forged ZYK530 magnesium alloy after aging heat treatment

In this experiment, after solution treatment of ZYK530 magnesium alloy at 480 °C × 8 h, no I-Mg_3Zn_6Y phase and Z-$Mg_{12}YZn$ phase were found in XRD analysis. In addition to α-Mg, there was only W-$Mg_3Zn_3Y_2$ phase in the alloy. The main reason is that the phase transformation temperature of the I-Mg_3Zn_6Y phase is 445 °C. Therefore, during the solid solution treatment of 480 °C × 8 h, the I-Mg_3Zn_6Y phase will transform into the Z-$Mg_{12}YZn$ phase, while the Z-$Mg_{12}YZn$ phase has an 18R microstructure, and the phase transformation temperature is 453 °C. During the solution treatment at 480 °C, the W-$Mg_3Zn_3Y_2$ phase is face centered cubic structure, which has better stability than the Z-$Mg_{12}YZn$ phase[17 – 19, 24, 25]. Therefore, it can be seen from the SEM images that the shape of the whole grid formed by the primary phase has little change. $Mg_{24}Y_5$ phase and Mg_2Zn_3 phase are non-equilibrium phases [21], during solution treatment, these two phases decompose and dissolve in the Mg matrix. Therefore, after solution heat treatment at 480 °C × 8 h, I-Mg_3Zn_6Y and Z-$Mg_{12}YZn$ phase in the die forged ZYK530 Mg alloy are not detected, as shown in Fig. 5.

According to related literature [15], the I-Mg_3Zn_6Y phase has an icosahedral quasicrystalline structure, which has a good bonding with the Mg matrix, which is conducive to improve the mechanical properties of the alloy; the W-$Mg_3Zn_3Y_2$ phase has a face-centered cubic structure, which is inconsistent with the close-packed hexagonal structure of the Mg matrix, resulting in weak atomic bonding force with the Mg matrix, which is easy to reduce the tensile strength of the alloy, but it can increase the compressive capacity of the alloy; the Z-$Mg_{12}YZn$ phase has a good binding force along the prism direction of the matrix, which plays an important role in improving the plastic deformation of bulk Mg alloys, which plays an important role in improving the plastic deformation of bulk Mg alloys, but the hardening and pinning effect of Z-

$Mg_{12}YZn$ relative to the alloy is less than that of I-Mg_3Zn_6Y and W-$Mg_3Zn_3Y_2$ phase due to the accumulation of dislocations, the hardening and strengthening effect of Z-$Mg_{12}YZn$ relative to the alloy is small [25].



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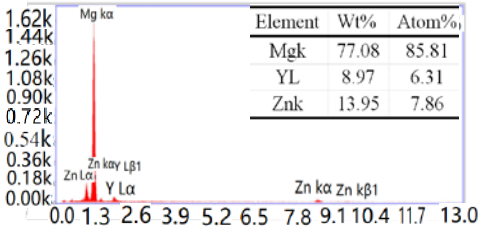

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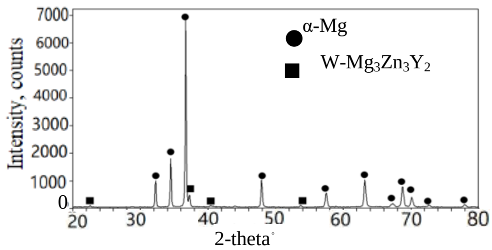

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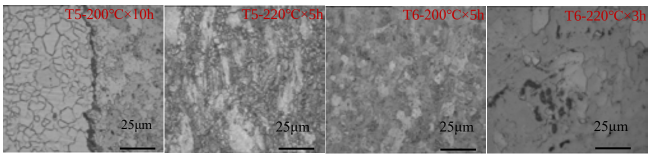
Fig. 5. a – SEM image; b, c – XRD spectrum of ZYK530 Mg alloy after solution treatment at 480 °C × 8 h

Fig. 6 shows the microstructure after the best treatment under four different process conditions.



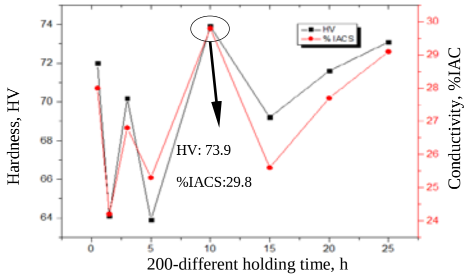
a b c d

Fig. 6. Microstructure of as-forged ZYK530 magnesium alloy after aging heat treatment

It can be seen from Fig. 4 that after the die-forged ZYK530 Mg alloy is artificially aged at T5-200 °C × 10 h, the composition of the phases in the alloy is the same as that of the untreated phase, but the diffraction peaks of the three ternary phases are significantly reduced, in which the peak values of I-Mg_3Zn_6Y and Z-$Mg_{12}YZn$ are significantly reduced; but the alloy grains have been significantly refined, and the uniformity of the grains has been improved to a certain extent, on the other hand, after being heat treatment at T5-220 °C × 5 h, the second phase in the alloy is mainly composed of I-Mg_3Zn_6Y, with a small amount of W-$Mg_3Zn_3Y_2$ phase and Zr phase; after solution aging heat treatment, XRD only detected W-$Mg_3Zn_3Y_2$ phase and a small amount of $MgZn_2$ phase. During the solution aging heat treatment process (T6-200 × 5 h and T6-220 × 3 h), as shown Fig. 4, the volume fraction of the precipitated phases in the alloy changes complicatedly with the solution aging heat treatment temperature and holding time, and the binding ability of these precipitated phases with the matrix is different, which has an important influence on the mechanical properties and electrical conductivity of the alloy.

3.2. The evolution of microhardness and electron-conductivity

Fig. 7 presents the influence curve of different heat treatments on microhardness and electron conductivity.



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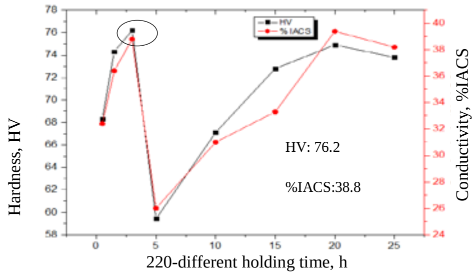

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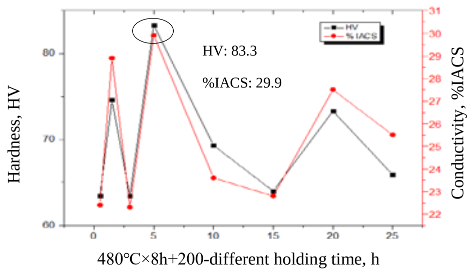

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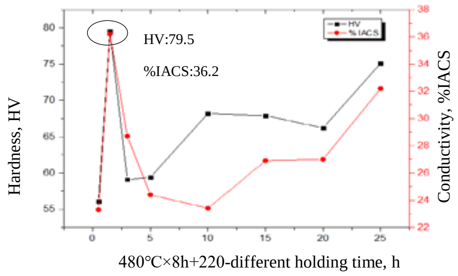

d

Fig. 7. The curves of microhardness and electron-conductivity changes under different heat treatment

With the increase of holding time, the microhardness and electrical conductivity of die forged ZYK530 magnesium alloy have the same change trend, both increase in oscillation, and at the position where the microhardness reaches the maximum value, the electro-conductivity is also at the peak position. With the extension of holding time, the evolution trend of microhardness and electro-conductivity of the alloy is similar.

Generally speaking, the finer the grains of the alloy, the greater the microhardness; the greater the hardness and quantity of the second phase in the alloy, and the greater the concentration of solid solution atoms in the metal matrix, the higher the microhardness corresponding to the alloy [9]. The grain size of untreated ZYK530 alloy is seriously uneven, which makes the hardness of the alloy cross section uneven, as shown in Fig. 2. After the aging process at 200℃×10h, the microhardness and electro-conductivity of the alloy increased by 1.8 % and 12.5 %, respectively; while heat treatment at 220℃×5h, the Z-$Mg_{12}ZnY$ phase in the alloy disappears, and the microhardness and electron-conductivity of the alloy increase by 5 % and 46.4 %, respectively; after solution aging at 480℃ ×8 h + 200℃ × 5 h, the microhardness and electro-conductivity of the alloy rose 14.7 % and 12.8 %, respectively; after 480℃ × 8h + 220℃ × 3h, the microhardness and electron-conductivity of the alloy improved 9.5 % and 36.6 %, respectively. When the aging process is 220 ℃ × 3 h, its electro conductivity is the highest, but the improvement of its mechanical properties is limited, as shown in Fig.7c; however, when the artificial aging heat treatment is 480℃ × 8 h + 220 ℃ × 3 h, the microhardness and electrical conductivity increased. So, combined with the production practice, it can be determined that 480 ℃ × 8 h + 220 ℃ × 3 h is the optimum treatment process of die forging ZYK530 alloy.

3.3. Relationship between hardness and conductivity

According to the Pearson correlation coefficient formula, the microhardness and electro-conductivity correlation coefficient of die-forged ZYK530 alloy under different heat treatment conditions were characterized. The correlation coefficient between hardness and electrical conductivity $\rho(x,y)$ is between 0.78876 ~ 0.9257, R-square is 0.55917 ~ 0.8949, which shows that different holding time has the same trend on the microhardness and electron-conductivity changes of die forged ZYK530 alloy, belonging to extremely strong or strong positive correlation, and the result of data fitting is good, as shown in Fig. 8. It can be seen that the electron-conductivity of the alloy is linear with the hardness of the alloy. The relationship between the two is obtained by data fitting, where x is the Vickers hardness of the alloy, and y is the electron-conductivity of the alloy.

There are a lot of dispersed strengthening phases in ZYK530 Mg alloy during the heat treatment, and some phases decompose or diffuse under certain temperature conditions, so the phase transformation of the alloy is complex. The electrical conductivity of the alloy is affected by matrix, grain boundary structure, precipitated phase and coarse second phase. In the process of aging heat treatment, the main factors affecting the electrical conductivity include: 1) the concentration of solute atoms in the matrix is low, the degree of lattice distortion is reduced, the scattering effect on electrons is weakened, and the conductivity is improved; 2) the precipitation phase precipitates from the supersaturated solid solution, which makes the alloy structure change from single phase transformation to multiphase, and produces additional scattering to the electrons, and the conductivity will decrease. The final conductivity of the alloy makes the superposition of the above two effects [15]. The relationship between electrical conductivity and alloy elements in the aging process (1) [16]:

$$\sigma_{M(t)} = 1/\rho_{M(t)} = \frac{1}{\rho_0 + r_{Zn}x_{Zn(t)} + r_Y x_{Y(t)}}, \qquad (1)$$

where $\sigma_M\,(t)$ is the matrix conductivity; $\rho_M(t)$ is the matrix resistance; ρ_0 is the matrix resistance without alloy elements; t is the aging time; $x_{Zn}\,(t)$ and $X_Y\,(t)$ are the concentrations of Zn and Y in the matrix respectively. Only Zn and Y alloy elements dissolved in the matrix are considered in the above formula. It can be seen from the formula that the conductivity increases with the decrease of solute concentration in the alloy.

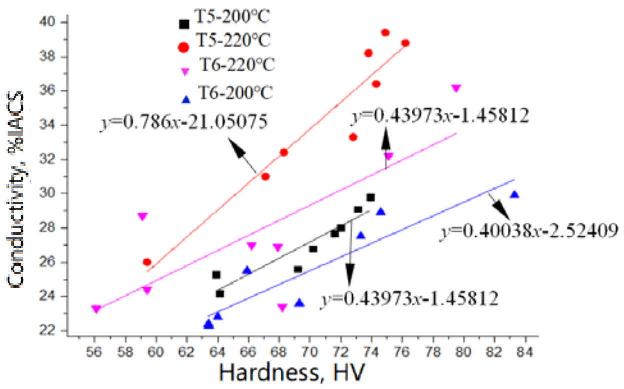

Fig. 8. The fitting curve of conductivity and hardness under different process conditions

3.4. Discussion and analysis

The electro-conductivity of the alloy has a bearing on the dispersion level of electron-conduction by holes, grain boundaries, dislocations, so solid atoms and second phases. The effect of solid solution atoms on the conductivity of alloys is the most severe, which is generally several orders of magnitude larger than other factors. Therefore, it is generally believed that the precipitation of solution atoms from the matrix can significantly improve the electrical conductivity of the alloy[9,19]. The effect of Zn and Y on the electrical conductivity of Mg-Zn-Y-Zr alloy mainly includes two aspects:

1. The Zn atoms dissolved in the Mg matrix lead to the decrease of the electrical conductivity of the alloy, which is due to the different chemical properties of the dissimilar atoms and the matrix atoms, such as the size and valence, which leads to the lattice deformation of the matrix and increases the electron dispersion effect;

2. For the Mg alloy containing Y, Zn forms a ternary system with Mg and Y, which will also cause lattice distortion, which will have a certain impact on the electron-conductivity of the alloy. However, if the precipitated phase's size is large and the content is low, the lattice distortion caused by the second phase is much smaller than the scattering effect of solute atoms in the magnesium matrix, which can be ignored [9, 19].
3. Zr and Mg have a good lattice matching relationship. As the core of heterogeneous nucleation, Zr only plays a role in grain refinement, but does not change the structure of the alloy phase. Therefore, Zr has no contribution to electrical conductivity.

Zn, Y and Mg elements in the as-forged ZYK530 Mg alloy form I-Mg_3Zn_6Y, Z-$Mg_{12}YZn$, W-$Mg_3Zn_3Y_2$ and a small amount of Mg_2Zn_3 phase, $Mg_{24}Y_5$ and uncertain phase. I-Mg_3Zn_6Y and Mg matrix have good matching, which can effectively improve the hardness, toughness and corrosion resistance of the alloy. However, the electrical conductivity and heat conduction of the I-Mg_3Zn_6Y phase are close to insulation [25]. Thus, the formation of the Mg-Zn-Y ternary phase reduces Zn content in the Mg matrix, but the formation of these second phases causes a lot of distortion of the matrix lattice and increases the dispersion action of electrons, and therefore, the electron-conductivity of the original sample is lower than that of the heat-treated sample. Due to the uneven force during the die forging deformation of the sample, the grain size of the alloy is uneven, which results in the average microhardness of the alloy being worse than that of the heat-treated alloy.

After solid solution treatment at 480℃×8h, Zn diffuses into the magnesium matrix due to the dissolution of the I-Mg_3Zn_6Y phase and the Z-$Mg_{12}YZn$ phase in the matrix, which increases the Zn content in the matrix. Moreover, the atomic radii of Mg, Zn and Y is different, the enrichment of Y will lead to the expansion of atomic layer spacing, while the enrichment of Zn will lead to the decrease of atomic layer spacing, and the expansion degree is greater than the reduction degree [19], increasing the electron scattering effect, and then after aging treatment of 200 ℃ × 5 h, the alloy is mainly composed of a large number of black fine precipitates, while these black phases may be W' phase, as shown in Fig. 6c, W' phase is considered to be the W-$Mg_3Zn_3Y_2$ phase precipitated from the matrix. The W phase is cubic structure and has a poor coherent relationship with Mg matrix, while W' phase is semi coherent with the Mg matrix, which improves the hardness and toughness of the alloy matrix to a certain extent [20]; At the same time, due to the precipitation of W 'phase, the number of Zn and Y atoms in the Mg matrix decreases, which results in the reduction of lattice imperfection and the increase of electro-conductivity. The $MgZn_2$ phase content in the alloy is less, the scattering effect of solute atoms in the Mg matrix can be neglected. After solution aging treatment at 480 ℃ × 8 h + 220 ℃ × 3 h, the amount of fine black W′ precipitates in the alloy decreases as expected, as shown in Fig. 6 d, the microhardness of the alloy is lower than that of the alloy treated at 480 ℃ × 8 h + 220 ℃ × 5 h. However, due to the decrease of W′ precipitates, the reduction degree of Zn and Y atoms in the matrix decreases, which makes the electro-conductivity of the alloy significantly improved.

After the die forging sample is directly subjected to T5-200 ℃ × 10 h artificial aging treatment, the alloy grains are relatively uniform, thus reducing the internal stress of the alloy, and the unknown phase, $Mg_{24}Y_5$ phase and Mg_2Zn_3 phase decompose in the die forging alloy. At this time, the second phase of the alloy is mainly composed of I-Mg_3Zn_6Y, W-$Mg_3Zn_3Y_2$ and Z-$Mg_{12}ZnY$ phases. Zn atoms in the matrix have a certain increase, but there is an I-Mg_3Zn_6Y phase with poor thermal and electrical conductivity in the alloy, and the precipitates of the Z-$Mg_{12}ZnY$ phase change the lattice structure of the matrix, so its hardness and electrical conductivity are only increased by 1.8 % and 12.5 %, respectively. After T5-220 ℃ × 3 h artificial aging treatment, the alloy mainly consists of I-Mg_3Zn_6Y and W-$Mg_3Zn_3Y_2$ phases, but Z-$Mg_{12}ZnY$ phase is not detected. It is preliminarily judged that the phase is dissolved in the matrix, so the amount of precipitated phase is reduced, and the influence on lattice distortion is reduced. The incompleteness of the solid solution lattice is greatly reduced, which makes the electrical conductivity of the alloy increase by 46.4 %; the quasicrystal I-Mg_3Zn_6Y phase, which has good coherent relationship with the magnesium matrix, has a certain degree of dissolution. Therefore, the improvement of plasticity and toughness of the alloy is less than that of T5-200 ℃ × 10 h, which is only 5 % higher than that of the original sample.

In conclusion, combined with the actual production, the best heat treatment process of die forging ZYK530 Mg alloy is 480 ℃ × 8 h + 220 ℃ × 3 h.

4. CONCLUSIONS

There are relatively few studies on the electron-conductivity and microhardness of magnesium alloy. The analysis and research on the correlation between the microhardness and electro-conductivity of die forged ZYK530 magnesium alloy by heat treatment show that heat treatment has an important effect on the hardness and conductivity of ZYK530 magnesium alloy. The experimental results and process provide some experimental basic data and methods for the development of good corrosion resistance and high performance magnesium alloy, it provides an important experimental reference for the study of corrosion resistance of magnesium alloy. The main conclusions are as follows:

1. With the prolongation of holding time, the electro-conductivity and microhardness show the same change trend, and both increase in a surge manner. After reaching the maximum value, the electro-conductivity decreases in a fluctuating manner, and there is a strong linear positive correlation between the microhardness and the electro-conductivity, and the fitting results of electro-conductivity and microhardness are in good matching with the experimental results;
2. Combined with the actual production, when the solution aging treatment is 480 ℃ × 8 h + 220 ℃ × 3 h, the maximum microhardness of the alloy is 79.2 HV, the electro

conductivity is 36.2 % IACS, and the comprehensive performance is the best, which is optimum heat treatment process.

Acknowledgments

The research was financially supported by Leshan Normal University talent introduction project (Grant No. XJR17003); Key scientific research projects of university discipline construction (Grant No. LZD030) and Horizontal subject (Grant No.801619400); Study on high strength and corrosion resistant aluminum alloy for Aerospace (Grant No.208000518); Key research projects of Leshan Science and Technology Bureau (20ZDYJ0267).

REFERENCES

1. **Kainer, K.U., Mordike, B.L.** Magnesium Alloys and Their Applications (Master thesis) *New York: Wiley Online Library*, 1999.
2. **Luo, A.A.** Magnesium Casting Technology for Structural Application *Journal of Magnesium and Alloys* 1 (1) 2013: pp. 2 – 22. https://doi.org/10.1016/j.jma.2013.02.002
3. **Eliezer, A., Gutman, E.M.** Corrosion Fatigue of Die-cast and Extruded Magnesium Alloys *Journal of Light Materials* 1 (3) 2001: pp.179 – 186. https://doi.org/ 10.1016/S1471-5317(01)00011-6
4. **Lin, G.Y., Peng, D.S., Zhang, H., Zhao, Y.W.** Study on Corrosion Resistance of AZ91D Magnesium Alloy Ingots *Mineral Engineering* 21 (3) 2001: pp. 79 – 81. https://doi.org/CNKI:SUN:KYGC.0.2001-03-023
5. **Wen, L.H., Ji, Z.S., Li, X.L.** Effect of Extrusion Ratio on Microstructure and Mechanical Properties of Mg-Nd-Zn-Zr Alloys Prepared by a Solid Recycling Process *Materials Characterization* 59 (11) 2008: pp. 1655 – 1660. https://doi.org/10.1088/2053-1591/ab0b16
6. **Doege, E., Droder, K.** Sheet Metal Forming of Magnesium Wrought Alloys Formability and Process Technology *Journal of Materials Processing Technology* 115 (1) 2001: pp. 14 – 19. https://doi.org/10.1016/S0924-0136(01)00760-9
7. **Mordike, B.L., Ebert, T.** Magnesium Properties Applications Potential *Materials Science and Engineering* 302 (1) 2001: pp. 37 – 45. https://doi.org/10.1016/S0921-5093(00)01351-4
8. **Huang, X.G.** Application of Magnesium Alloy in Thermal Simulation Design of LED Lamps *China's High Tech Enterprises* 340 (25) 2015: pp. 62 – 63. https://doi.org/JournalArticle/5b3bc15ac095d70f008d0c45
9. **Pan, H.C., Pan, F.S., Zhang, L., Peng, J., Wu, L., Wu, B.J., Huang, M.N., Zhao, H.Y.** Heat Resistant Mg-Al-Sr Alloys with High Electrical Conductivity *Rear Metal Materials and Engineering* 44 (3) 2015: pp. 727 – 732. https://doi.org/CNKI:SUN:COSE.0.2015-03-041
10. **Zheng, X., Cahill, D.G., Krasnochtchekova, P., Averback, R.S., Zhao, J.C.** High-throughput Thermal Conductivity Measurements of Nickel Solid Solutions and the Applicability of the Wiedemann–Franz Law *Acta Materialia* 55 2007: pp. 5177 – 5185. https://doi.org/10.1016/j.actamat.2007.05.037
11. **Chen, Z.H.** Wrought Magnesium Alloy. *Chemical Industry Press.* 2005.6
12. **Cao, H.X., Long, S.L.** Compressive Deformation Behavior of Mg Alloy in Interact-multiple Adscititious Fields *China Machinery Engineering* 18 (3) 2007: pp. 361 – 364. https://doi.org/JournalArticle/5aea2b85c095d713d8a37ec1
13. **Cao, F.H., Chen, C., Xu, Y.H.** Evolution of Microstructure and Properties ZYK530 Magnesium Alloy During Extrusion-Forging Compound Forming *IOP Conference Series Materials Science and Engineering* 2019: pp. 1 – 8. https://doi.org/10.1088/1757-899X/711/1/012001
14. **Feng, Y., Mao, P.L., Liu, Z., Wang, Z., Zhang, S.B., Wang, F.** Effect of yttrium content on hot tearing susceptibility of MgZn4.5YxZr0.5 alloys *The Chinese Journal of Nonferrous Metals* 27 (10) 2017: pp. 1970 – 1980. https://doi.org/10.19476/j.ysxb.1004.0609.2017.10.02
15. **Yang, H.H., Hu, X.H., Wang, S.H., Feng, Z.H.** Study on Relationship of Strength, Hardness and Electrical Conductivity of 7085 Aluminum Alloy Forgings *Aluminum Processing* 207 (4) 2012: pp. 37 – 40. https://doi.org/CNKI:SUN:LJGO.0.2012-04-011
16. **Starink, M.J., Li, X.M.** A Model for the Electrical Conductivity of Peak-aged and Over-aged Al-Zn-Mg-Cu Alloys *Metallurgical and Materials Transactions A* 34A (4) 2003: pp. 899 – 911. https://doi.org/10.1007/s11661-003-0221-y
17. **Shen, C., Zhang, X.B., Xue, Y.J., Wang, Z.Z.** Effect of Heat Treatment on Microstructure and Corrosion Behavior of Mg-Y-Cu-Zr Magnesium Alloy with LPSO Structure *Journal of Materials Heat Treatment* 36 (5) 2015: pp. 137 – 142. https://doi.org/10.13289/j.issn.1009-6264.2015.09.024
18. **Yu, T.** A Study on Microstructure and Properties of Magnesium Alloys with Special Structural Phase (Doctor thesis). *East China Jiaotong University.* 2015.6.
19. **Ma, Z.N., Jiang, M., Wang, L.** First-principles Study of Electronic Structures and Phase Stabilities of Ternary Intermetallic Compounds in the Mg-Y-Zn *Acta Physica Sinica* 64 (18) 2015: pp. 1 – 7. https://doi.org/7.10.7498/aps.64.187102
20. **Xue, D.S., Liu, L.L., Sun, W.** Electron Microscopy Study of Microstructural Variations for the As-cast $Mg_{96}Zn_3Y_1$ Alloy Subjected to High-temperature Heat Treatment *Journal of Chinese Electron Microscopy Society* 30 (6) 2011: pp. 488 – 493. https://doi.org/10.1007/s12598-011-0191-y
21. **Zhang, Q., Li, Q.N., Jing, X.T., Zhang, X.Y.** Microstructure and Mechanical Properties of Mg-10Y-2.5Sm Alloy *Journal of Materials Heat Treatment* 31 (1) 2011: pp. 24 – 28. https://doi.org/CNKI:SUN:JSCL.0.2011-01-006
22. **Zhang, Z.Y., Wu, X.L.** Research on Heat Dissipation Structure of High Power LED *Intelligent Building & City Information* 1 2015: pp. 71 – 72. https://doi.org/10.16520/j.cnki.1000-8519.2017.10.017
23. **Liu, G., Zhang, Z.Z., Chen, Q., Zhang, H., Yin, C.H., Zhang, S.M.** Effects of Cooling Rate on Microstructure and Properties of Mg-5Zn-1Y-0.6Zr Alloy *Special Casting and Nonferrous Alloys* 29 (1) 2009: pp. 981 – 983. https://doi.org/10.3870/tzzz.2009.11.001
24. **Zhen, M.Y., Wu, K., Qiao, X.G., Li, S.B., Hu, X.S.** Quaiscrystals Containing Magnesium and High Performance Magnesium Alloys *Materials Science and Technology* 12 (6) 2004: pp. 666 – 672. https://doi.org/10.1109/JLT.2003.821766

25. **Jun, Y.Y., Woo, J.K.** Effect of I(Mg_3YZn_6), W($Mg_3Y_2Zn_3$) and LPSO($Mg_{12}ZnY$) Phases on Tensile Work-hardening and Fracture Behaviors of Rolled Mg-Y-Zn Alloys *Journal of Materials Research and Technology* 8 (2) 2019: pp. 2316 – 2325. https://doi.org/10.1016/j.jmrt.2019.04.016