Effects of Reheating Temperature and Time on the Microstructure and Mechanical Properties of Thixoformed ZW21 Alloy

Ti Jun Chen*, Hui Guo, Ying Ma and Yuan Hao

State Key Laboratory of Advanced Processing and Recycling of Nonferrous Metals, Lanzhou University of Technology, Lanzhou 730050, China

The effects of reheating temperature and time on the microstructure and mechanical properties of thixoformed ZW21 alloy were investigated. The results indicate that the ZW21 alloy is suitable for thixoforming in view of its thixoformability and the resulting mechanical properties. The reheating temperature and duration mainly affect the microstructure, including the size and fraction of primary particles, the microstructure compactness, the solubilities of the solute elements and W phase content, and thus the mechanical properties of the thixoformed alloy. The effects of the reheating temperature are larger than that of the reheating time. These two parameters have an optimum critical value, and values less than or higher than this value decrease the mechanical properties. The appropriate reheating technique is heating for 70 min at 913 K, and the resulting ultimate tensile strength, elongation, and hardness can be up to 238 MPa, 19.4%, and 58 HV, respectively. As the reheating temperature or reheating time increases, the fracture regime has a tendency to change from intergranular mode to transgranular mode and finally to intergranular mode again. [doi:10.2320/matertrans.M2015151]

(Received April 17, 2015; Accepted June 8, 2015; Published July 27, 2015)

Keywords: ZW21 magnesium alloy, thixoforging, microstructure, mechanical properties, fracture regime

1. Introduction

As the lightest metallic structural materials, magnesium alloys are potentially widely applicable in the automobile and aerospace industries.1) However, the mechanical properties of commonly used magnesium alloys are relatively low and cannot fulfill the requirements of many applications. It has been reported that Mg-Zn-Y system alloys always have high mechanical properties.2–6) A Mg$_{97}$Y$_2$Zn$_1$ (in mol%) alloy produced by rapid solidified powder metallurgy has a yield stress of greater than 610 MPa and an elongation of 5%.3,4) A Mg-10Y-2Zn (all of the percentages refer to weight percentage if not specified otherwise) alloy also processed by rapidly solidified powder metallurgy exhibits a tensile strength of 520 MPa.5) As-cast Mg-Zn-Y alloys have yield stresses from 180 to 480 MPa, depending on their composition.6) Thus, the Mg-Zn-Y system is an ideal candidate for developing high-performance magnesium alloys, and investigation of this system is one of the hottest topics in the development of new magnesium alloys.7,8)

The authors have developed a new Mg-Zn-Y alloy named ZW21, and the as-cast ZW21 alloy has an ultimate tensile strength of 205 MPa, an elongation of 18.25%, and a hardness of 50 HV.9) After being properly heat treated, these three mechanical properties can be improved to 243 MPa, 23.75%, and 68.7 HV, respectively.10) Further, the content of high-cost rare earth elements is only 1.5%, and the content of large-density elemental Zn is about 2%. Thus, this alloy not only has higher mechanical properties but is also lower in cost and lighter in weight compared to the other commonly-used congeneric alloys. Thus, it has larger application potential in common civil fields. Given the commonly used forming technology of Mg-Zn-Y alloys5) and the good elongation of the ZW21 alloy, this alloy may be more suitable for plastic processing. However, components produced by plastic processing always have high cost, and it is difficult to fabricate components with complicated shapes. The casting of deforming alloys is a promising method, and the most popular method is thixoforging.11)

Thixoforming, a relatively new metal-forming technology, can significantly improve the mechanical properties of aluminium alloys by decreasing or even eliminating porosity and gas pores, and a large number of thixoformed aluminium-alloy components have been used in automobiles.11,12) In addition, thixoformed components can be heat treated to further improve their mechanical properties. In theory, thixoforming will also be a good way to improve the mechanical properties of magnesium alloys.

Unfortunately, the application of thixoforming to magnesium alloys has been relatively slow compared to its application to aluminium alloys, and only one technique, thixomoulding, has been used commercially.12) Most of the existing investigations have focused on the preparation of semisolid non-dendritic ingots.13–18) Only a few papers have considered the microstructures and mechanical properties of magnesium alloys thixoformed under some given processing parameters.16–18) A study on the detailed effects of processing parameters on the microstructure and mechanical properties has not been found. In addition, for an alloy to be thixoformed, it must fulfill the primary requirements, such as a wide solidification interval, a wide processing temperature window and a low sensitivity of the solid fraction to temperature.19) Therefore, the thixoformability of the ZW21 alloy is examined first in this work. Then, the effects of two main processing parameters, the reheating temperature and the reheating time, on the microstructure and tensile properties are discussed in detail.

2. Experimental Procedure

The nominal composition of the ZW21 alloy used here was Mg-2Zn-1Y-0.5Nd-0.5Sn-0.3Zr-0.05Ca (in mass%). This
Effects of Reheating Temperature and Time on the Microstructure and Mechanical Properties of Thixoformed ZW21 Alloy

The ZW21 alloy was prepared with pure Mg, Zn and Sn metals, and Mg-30Y, Mg-30Nd and Mg-30Zr master alloys. During melting, a JDMJ refining agent (a type of melt-refining agent for magnesium alloys developed by Shanghai Jiaotong University, China) and a special covering agent (to prevent oxidation of the melt) for Mg–RE alloys were employed. The prepared melts were finally poured into a permanent mold with a cavity of $45\text{mm} \times 150\text{mm}$ at 983–993 K. Several casting rods were obtained by repeating this experimental process.

The casting rods were machined into small ingots with dimensions of $43\text{mm} \times 30\text{mm}$ to act as the starting ingots for thixoforming. To evaluate this alloy’s thixoformability, some ingots were cut into small specimens (fan-shaped specimens) with dimensions of a quarter of an $43\text{mm} \times 10\text{mm}$ rod. Then, they were heated for 30 min at temperatures ranging from 893 K to 919 K and water-quenched. Subsequently, they were finished, polished, etched using 4% HNO$_3$ aqueous solution and observed with a Mef-3 optical microscope (OM). To examine the solid/liquid fraction, the obtained images were analyzed using Image-Pro Plus 6 software. At least three images with a magnification of 200 times were analyzed for each specimen. To verify the semisolid interval, the casting alloy was examined with a Pyris Diamond TG/DTA differential thermal analyzer (DTA).

For thixoforming, the small ingots with dimensions of $43\text{mm} \times 30\text{mm}$ were reheated for a given time at a given semisolid temperature, placed in a forge mould with a cavity of $50\text{mm} \times 60\text{mm}$ and forged under a pressure of 160 MPa on a Y32-60T hydraulic machine. To prevent oxidation during reheating, each ingot was placed in a specific container, and Ar gas was flowed into it. The detailed processing parameters are shown in Table 1. The mould temperature was 523 K. To examine the temperature variation of the ingot during reheating, a hole was drilled in the center of an ingot, and a thermocouple was mounted in it. Five tensile specimens were machined from the center region of each thixoformed product parallel to the press direction. The dimensions of the tensile specimens are shown in Fig. 1. A WDW-100D material testing machine was used to examine the tensile properties. The fracture surfaces and fracture surface side-views were examined with a QUANTA FEG450 scanning electron microscope (SEM) and the OM, respectively. To analyze the phase constituents and microstructures and to examine hardness of the thixoformed products, a small specimen (with dimensions of $10\text{mm} \times 10\text{mm} \times 10\text{mm}$) was cut from each product, finished and polished. Then, the specimens were analyzed using a D/MAX-2400 X-ray diffractometer (XRD), observed with the SEM using the back-scattered electron imaging technique and analyzed with energy dispersive spectrometer (EDS). Subsequently, they were etched using 4% HNO$_3$ aqueous solution and observed with the Mef-3 OM. The results indicate that the microstructures of the thixoformed products were composed of primary particles and intergranular secondarily solidified structures (SSSs). The size and fraction of primary particles were examined using Image-Pro Plus 6 software. Finally, the hardness was examined using an HBRVU-187.5 Brinell-Rockwell-Vickers optical hardness tester.

### Table 1 Processing parameters used in this work.

<table>
<thead>
<tr>
<th>Reheating temperature (K)</th>
<th>Reheating time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of reheating time</td>
<td>898, 903, 908, 913, 918</td>
</tr>
<tr>
<td>Effect of reheating time</td>
<td>913</td>
</tr>
</tbody>
</table>

Figure 1 Schematic of a tensile testing specimen.

3. Results and Discussion

3.1 Thixoformability of the ZW21 alloy

Figure 2 shows that the microstructure of the as-cast ZW21 alloy is composed of small equiaxed grains (Fig. 2(a)) and that the grains are separated by white eutectic structures (Fig. 2(b)). The average grain size is about 57 µm. Eutectic structures always exist in a divorced form, and the white phase in Fig. 2(b) is W ($\text{Mg}_3\text{Zn}_3(\text{Y}, \text{Nd})_2$). The DTA results indicate that the liquidus and solidus are 921 K and 866.58 K, respectively (Fig. 3). Namely, the semisolid temperature interval of the ZW21 alloy is about 45°C. Figure 4 shows that the temperature in the center of the starting ingot does not reach the given semisolid temperature of 913 K until it is heated for 53 min. To ensure that the temperature reached the given value, the reheating time was set to 60 min. The resulting semisolid microstructure is shown in Fig. 5. The solid primary particles are in spheroidal form and uniformly suspended in the liquid phase. The average particle size is 70 µm. That is, the equiaxed grains with a size of 57 µm evolve into spheroidal particles with a size of 70 µm after partial remelting at 913 K. This result is consistent with the conclusion of the investigations on other magnesium alloys, where a semisolid ingot with spheroidal primary particles can be obtained when an as-cast ingot with a grain size of less than 100 µm is partially remelted. One primary particle in the semisolid microstructure originates from two or more equiaxed grains in the as-cast microstructure, and the primary particle size is always larger than the equiaxed grain size. This means that the as-cast ZW21 alloy has good formation ability of the semisolid nondendritic microstructure and that the as-cast ingots are suitable as starting ingots for thixoforming in view their semisolid microstructure.

Figure 6 presents the variation of solid fraction with reheating temperature. It shows that the temperature is varied from 901 K to 917 K to obtain a solid fraction within the range where thixoforming is commonly used (0.4–0.6). That is, the processing temperature window is 16°C, and the sensitivity of solid fraction to temperature is 0.0125°C$^{-1}$. 
According to the accepted criteria for judging the thixoformability of an alloy, the semisolid temperature interval must not be larger than 150°C, the sensitivity of the solid faction to temperature must be less than 0.015°C⁻¹, and the processing temperature window must be larger than 6°C. The ZW21 alloy completely fulfills these requirements and is thus suitable for thixoforming.

3.2 Effects of reheating temperature on the microstructure and mechanical properties

3.2.1 Effect on microstructure

Figure 7 gives the microstructures of the ZW21 alloys thixoforged at different reheating temperatures (reheating time of 60 min). It shows that all of the microstructures are composed of primary particles and intergranular SSSs. However, three phenomena arise as the reheating temperature is increased. The first phenomenon is that the amount of SSSs increases while the amount of primary particles decreases.
The second is that the primary particles gradually spheroidize. The third is that the size of the pool-like SSSs entrapped within the primary particles increases, and a large one gradually forms at the center of the primary particle. The quantitative examination results shown in Fig. 8 also indicate that the primary particle size decreases slightly as the temperature rises from 898 K to 913 K.

It is well known that the reheating temperature mainly affects the liquid fraction of a semisolid microstructure. An increase in the reheating temperature must increase the liquid amount and thus increase the SSSs in the thixoformed product. In addition, it is reasonable to expect that the partial remelting of the primary particles due to the temperature increase must decrease the primary particle size. However, coarsening due to coalescence and Ostwald ripening is simultaneously accelerated due to the improved atom diffusion ability.\(^{13}\) Thus, the primary particle size only decreases slightly when the temperature increases from 898 K to 913 K and then increases slightly. Similarly, the coarsening of the entrapped liquid pools driven by the decreasing solid/liquid interface energy is also accelerated.\(^{22}\) Together with the increased partially remelted solid, the liquid pool size thereby increases, and a large one forms in the center region of the primary particles. In addition, partial remelting preferentially occurs at the corners and edges of the primary particles,\(^{20,21}\) so the primary particles become more spheroidal as the reheating temperature rises. It can be expected that the larger and more spheroidal the primary particles in the semisolid microstructure are, the larger and more spheroidal the primary particles in the thixoformed microstructure are when the solidification conditions are given. Based on these points, the results shown in Figs. 7 and 8 can be interpreted easily.

Figure 9 shows that the W phase content (in white) first decreases as the temperature increases from 898 K to 913 K and then increases again with a further increase in temperature. The quantitative examination more obviously shows this change (Fig. 10). The XRD results indicate that the intensities of the W-phase diffraction peaks all gradually become weak when the temperature rises from 898 K to 913 K and then become strong again (Fig. 11). This also
shows the change in the W phase content. It should be noted that this alloy has other phases such as Mg2Sn and Mg2Ca, besides the α-Mg and W phases. However, they were not detected by XRD due to their small amounts. This change in the W phase content depends on the variations of the solute contents, such as Zn, Y and Nd, in the primary particles and the liquid phase of the semisolid ingots prior to thixoforming.

According to the Mg-Zn binary phase diagram shown in Fig. 12, for the Mg-2% Zn alloy, the Zn content in the solid phase will decrease while that in liquid phase will increase as the temperature increases within the solidification interval. Therefore, the amount of Zn-enriched W phase should increase after solidification. However, the present result within the range of 898 to 913 K is contrary to this speculation. The reason is that the status of the present experiment and the status that the phase diagram reflects are different. The phase diagram is obtained in the equilibrium state, but in the present experiment, it is possible that the system has not reached the final solid-liquid equilibrium state when the ingot is heated for 60 min at temperatures of 898 to 913 K. The Zn content in the primary particles should be lower than the equilibrium value under these conditions. Thus, the Zn content increases with the reheating temperature due to the improved atom diffusion ability (Table 2). That is, the Zn content gradually approaches the final equilibrium value as the temperature increases. Table 2 indicates that the system reaches the equilibrium state when the temperature increases to 913 K, and so the Zn content then decreases with a further increase in temperature, obeying the phase diagram. Similarly, the variations of other solutes such as Y and Nd can also be interpreted using the same argument. The increases in the solute contents in the primary particles must result in their decreases in the liquid phase, and vice versa. Based on this analysis, the variation of the W phase content shown in Figs. 9 and 10 can be easily understood.

In summary, the reheating temperature has large effect on the microstructure of the thixoformed ZW21 alloy. The primary particles gradually become more spheroidal and the amount of SSSs increases as the temperature increases. Simultaneously, the eutectic W phase content decreases as the temperature increases from 898 K to 913 K, and then it increases. This change is attributed to the content variations of solute elements in the solid/liquid phases prior to thixoforming. The primary particle size only decreases slightly in the range of 898 to 908 K and then increases slightly. The size of the pool-like SSSs always increases.

### Table 2 Solute contents in the primary particles of the ZW21 alloys thixoformed at different reheating temperatures.

<table>
<thead>
<tr>
<th>Reheating temperature (K)</th>
<th>Zn</th>
<th>Y</th>
<th>Nd</th>
</tr>
</thead>
<tbody>
<tr>
<td>898</td>
<td>1.05</td>
<td>0.26</td>
<td>0.11</td>
</tr>
<tr>
<td>903</td>
<td>1.62</td>
<td>0.42</td>
<td>0.16</td>
</tr>
<tr>
<td>908</td>
<td>1.76</td>
<td>0.47</td>
<td>0.18</td>
</tr>
<tr>
<td>913</td>
<td>1.83</td>
<td>0.50</td>
<td>0.21</td>
</tr>
<tr>
<td>918</td>
<td>1.50</td>
<td>0.36</td>
<td>0.14</td>
</tr>
</tbody>
</table>

3.2.2 Effect on mechanical properties

Figure 13 shows that the mechanical properties, such as UTS, elongation, and hardness, all first increase as the temperature increases from 898 K to 913 K and then sharply decrease. In contrast, the variation in the hardness is relatively small. Undoubtedly, the decrease of the primary particles should have contribution to the improvement of the mechanical properties.
It can be expected that the liquid phase content should be relatively small when the alloy is thixoforged at 898 K, which was the lowest reheating temperature employed. In addition, the primary particles are quite large and irregular (Fig. 7(a)), so it can be expected that the mould-filling ability, especially the feeding ability for solidification shrinkage, is relatively poor. Thus, pores are easily formed. Figure 14(a) shows that there are many large-sized pores on the fracture surface due to the poor feeding ability. This is the main reason that the mechanical properties are relatively low. It can be assumed that the intergranular SSSs in which the pores exist are the weak points of this alloy, and so cracks preferentially develop within these structures during tensile testing (Fig. 15(a)) and only occasionally across the primary particles in local zones (marked by arrow A). That is, the fracture of this alloy belongs to the intergranular regime. As the reheating temperature increases, the liquid phase increases, and the primary particle size decreases; in particular, the particles become more spheroidal. The feeding ability is thereby improved, and porosity formation is depressed. The fracture surfaces show that the number of pores decreases significantly as the temperature increases (comparing Fig. 14(a)–(c)). Thus, the mechanical properties are improved (Fig. 13), but the fracture regime remains the same or even becomes better (Fig. 15(b)). The existing investigations proposed that the coarse interdendritic W phase in the as-cast W phase-containing alloys was harmful to mechanical properties.24,25) The reason is that the W phase is easy to crack, and cracks always propagate across the coarse W phase during tensile testing. Decreasing the size and amount of W phase can reduce the harm and improve the tensile properties, so the improvement of the tensile properties should also be attributed to the decreases of the size and amount of W phase (Figs. 9 and 10). In addition, it should be noted that the increased solubilities of Zn, Y, and Nd in the primary particles should also be beneficial for the improvement of mechanical properties.

As the reheating temperature further rises, the liquid content increases significantly and reaches up to about 67% (as shown by comparing Fig. 7(c) and (d) and Fig. 8). This increase decreases the advantages of semisolid forming and leads the solidification behavior of the semisolid ingot to be closer to that of liquid casting. The most obvious result is the increase in the porosity. Figure 14(d) shows that there are many pores on the fracture surface of the alloy thixoforged at a reheating temperature of 918 K (marked by arrows), but the side-view of the fracture surface indicates that the probability of crack propagation across the primary particles increases, and the fracture regime becomes a mixture of intergranular and transgranular modes (Fig. 15(c)). It is also found that cracks often develop across the large pool-like SSSs in the primary particle center (marked by arrow B). As discussed in Section 3.2.1, the liquid pools entrapped within the primary particles coarsen, and a large one always forms in the primary particles as the temperature increases. The liquid pools are isolated and do not connect with the other liquid phase, so pores are easily formed during solidification because there is no liquid to feed shrinkage. The larger the liquid pools, the harder to form. Thus, the pool-like SSSs should also be the weak points in the alloy, and cracks easily develop across the large pool-like SSSs during tensile testing. In addition, the size and amount of W phase increase again (comparing Fig. 9(c) and (d) and Fig. 10). That is, these three factors—the increase in porosity, the formation of large pool-like SSSs and the increase in the W phase, result in the decrease of the tensile properties. The formation of large pool-like SSSs is the main reason that the fracture regime turns from the intergranular mode to a mixture of intergranular and transgranular modes. In fact, the formation of large pool-like SSSs essentially leads to a less compact microstructure. Thus, it can be assumed that the liquid pools entrapped within the primary particles are undesirable for either the thixoformability of the semisolid ingot or the resulting mechanical properties.

Undoubtedly, the improvement of the compactness of the microstructure is also beneficial to increase the hardness. However, the decrease of the W phase content will decrease...
the hardness because the W phase is a hard and fragile phase and can increase hardness. The present result implies that the benefit of densifying the microstructure is larger than the harm caused by the decrease of the W phase content when the temperature increases from 898 K to 913 K, and the condition is the opposite when the temperature exceeds 913 K.

Therefore, it can be concluded that the UTS, elongation, and hardness first increase as the reheating temperature increases from 898 K to 913 K and then decrease. The increase should be mainly attributed to the increased density of the microstructure, the increase of the solute solubilities and the decrease of the W phase content. The decrease is ascribed to the formation of pores, the increase of the W phase content and the formation of large pool-like structures entrapped within the primary particles. Of course, the change of the primary particle size also affects the mechanical properties. Correspondingly, the fracture regime during tensile testing changes from intergranular mode to a mixture of intergranular and transgranular modes. This change is mainly due to the formation of the large pool-like structures.

3.3 Effects of reheating time on the microstructure and mechanical properties

3.3.1 Effect on microstructure

Figure 16 presents the microstructures of the ZW21 alloys thixoformed for different reheating times at 913 K. Together with Fig. 7(c), it can be found that the primary particles become more spheroidal and their size decreases while their fraction decreases as the time increases from 50 min to 70 min. Simultaneously, the size of the pool-like SSSs within the primary particles also increases. Subsequently, the primary particle size increases, their shapes become irregular again, and the fraction basically remains constant. All of these changes can be more obviously seen in the quantitative examinations in Fig. 17.

As discussed in Section 3.1, the temperature in the ingot center does not reach the given 913 K until it is heated for 53 min (Fig. 4). Previous investigations indicated that the semisolid did not reach the final solid-liquid equilibrium state although the temperature reached the given value. Thus, the amount of liquid phase in the semisolid ingot is lower than the equilibrium value when it is heated for 50 min, and thus the resulting amount of SSSs is small (Fig. 16(a)). The primary particles are also relatively large and irregular because they are only partially melted. As the reheating time increases, parts of the primary particles, especially their corners and edges, melt, which not only increases the amount of liquid but also causes the primary particles to become spheroidal and their sizes to decrease. Thus, the amount of SSSs in the thixoformed product increases, the primary particles become spheroidal, and their sizes become small (comparing Figs. 16(a), 16(b), and 7(c)). Simultaneously, the size of the liquid pools within the primary particles also increases due to the increased particle partial melting and the improved ripening of the liquid pools. The small change of the primary particle fraction after 70 min means that the semisolid system reaches its final solid-liquid equilibrium state. The main phenomenon that occurs after this is the coarsening of the primary particles, and the coarsening also causes them to be irregular. Therefore, it is easy to understand the microstructural changes after 70 min.

The SEM results indicate that the reheating time can also change the W phase content (Fig. 18). The content obviously decreases within 50–70 min and then almost does not change. The quantitative examination can further demonstrate this change (Fig. 19). Table 3 presents that the solubilities of the three solutes (the elements necessary to form the W phase: Zn, Y, and Nd) in the primary particles increase as the time is increased from 50 min to 70 min and then basically remain constant. Based on this result, the reason for the W phase content change can be thoroughly explained.

The reheating time also has a large effect on the microstructure of the thixoformed ZW21 alloy. Prolonging the time from 50 min to 70 min decreases the primary particle size, shape factor, fraction, and W phase content but increases the size of pool-like SSSs. Further prolonging the time increases the size and shape factor of the primary particles.

3.3.2 Effect on mechanical properties

Figure 20 shows that the mechanical properties of the thixoformed ZW21 alloys increase as the reheating time is prolonged from 50 min to 70 min and then decrease. The mechanical properties reach their highest values, a UTS of 238 MPa, an elongation of 19.4%, and a hardness of 58 HV,
when the time is 70 min. These values are higher than those of the permanent mold-cast ZW21 alloy, which means that the ZW21 alloy is suitable for thixoforming. Comparing Figs. 17 and 20, it can be found that the variation of the primary particle size is counter to that of the mechanical properties. Thus, the mechanism of grain refinement strengthening must affect the mechanical properties.

Figure 21 presents the fracture surfaces of the alloys thixoforged for different reheating times. The arrows indicate the pores. Together with Fig. 14(c), it can be seen that both the size and number of pores decrease as the time increases from 50 to 70 min (Fig. 21(a) and (b)), and then both increase again (Fig. 21(c) and (d)). Similarly, this result should also be related to the feeding ability during thixoforging. At the shortest time, 50 min, the feeding ability is quite poor due to the low liquid fraction, so pores are easily formed in the SSSs, which causes cracks to develop preferentially along the SSSs during tensile testing and only occasionally across the primary particles (marked by arrow A in Fig. 22(a)). As the time increases, the feeding ability is improved because of the increase of the liquid phase, the SSSs are gradually densified, and porosity is decreased. Thus, the mechanical properties are enhanced. The propagation path of cracks thereby changes from along the SSSs to across the primary particles (Fig. 22(b)). Similarly, the decrease of the W phase and the enhanced solution strengthening also contribute to the improvement of the mechanical properties. The formation of large pool-like SSSs is also ascribed to the change of the
4. Conclusions

(1) Given its thixoformability and resulting mechanical properties, the ZW21 alloy is suitable for thixoforming.

(2) The reheating temperature or time mainly alters the microstructure, including the size and fraction of primary particles, the microstructure compactness, solubilities and W phase content, and thus mechanical properties of the thixoformed ZW21 alloy. In contrast, the effect of the reheating time on the mechanical properties is larger than that of reheating temperature.

(3) The reheating temperature and time both have an optimum critical value, and a value less than or greater than this value decreases the mechanical properties. The appropriate reheating technique is heating for 70 min at 913 K, and the resulting UTS, elongation, and hardness can be up to 238 MPa, 19.4%, and 58 HV, respectively.

(4) As the reheating temperature or the reheating time increases, the fracture regime has a tendency to change from intergranular mode to transgranular mode, and finally to intergranular mode again.

Acknowledgement

The authors wish to express thanks for financial support from the Program for New Century Excellent Talents in University of China (Grant No. NCET-10-0023), the Program for Hongliu Outstanding Talents of Lanzhou University of Technology and the National Basic Research Program of China (Grant No. G2010CB635106).

REFERENCES