Study on quenching sensitivity of 7097 aluminum alloy

Peng Xie, Kanghua Chen, Songyi Chen, Shengping Ye, Huibin Jiao and Lanping Huang

1 National Key Laboratory of Science and Technology for National Defence on High-Strength Lightweight Structural Materials, Central South University, Changsha 410083, People’s Republic of China
2 Collaborative Innovation Center of Advanced Nonferrous Structural Materials and Manufacturing, Central South University, Changsha 410083, People’s Republic of China
3 Light Alloy Research Institute, Central South University, Changsha 410083, People’s Republic of China
4 Authors to whom any correspondence should be addressed.

E-mail: csuchenkh@126.com and sychen08@csu.edu.cn

Abstract

The time-temperature-property (TTP) and the time-temperature-transformation (TTT) curves of 7097 aluminum alloy are determined by interrupted quenching experiments in order to investigate the quench sensitivity. The quenching sensitive zone is 230–370 °C, and the nose temperature and transformation time are about 320 °C and 1.2 s, respectively. The evolution of quench-induced precipitates during different isothermal temperatures treatment has been observed by the transmission electron microscope. The number and size of quench-induced precipitates are gradually increased with the extension of isothermal holding time. Moreover, the quenching sensitivity of 7097 aluminum alloy is lower than that of 7055 aluminum alloy and 7050 aluminum alloy, but higher than that of 7085 aluminum alloy, and the influence of alloy composition on the quenching sensitivity is investigated.

1. Introduction

Al–Zn–Mg–Cu (7xxx series) aluminum alloys are widely used in transportation and aerospace due to their low density, high strength and super toughness [1, 2]. With the development of the aerospace industry, there is a trend to pursue higher strength and low quenching sensitivity properties for aluminum alloy thick section plates and forgings. It is well known that 7050 and 7085 aluminum alloys (AA7050 and AA7085) are successfully applied to the aircraft frame beam and other main bearing structures due to their high strength and low quenching sensitivity properties. Compared with conventional AA7050 and AA7085, the 7097 aluminum alloy (AA7097), a new generation of low-Cu containing high strength 7xxx series aluminum alloy, has been developed by Kaiser in 2015 [3]. However, little work has been carried out on the quench sensitivity of AA7097. It is well known that the slow quenching rate is harmful to mechanical properties due to decreasing matrix supersaturation [4]. In contrast, the rapid quenching rate is generally adopted to obtain higher mechanical properties. However, the rapidly quenching process will increase the tendency for the thick section plate/forging to develop high quenching residual stress, which is detrimental to the subsequent component dimension accuracy and properties. In particular, the central part of thick section plate/forging is inevitable with a slow quenching rate [5, 6]. Therefore, it is necessary to adopt appropriate quenching conditions to maximize the properties and minimize the residual stress in actual production [7].

The time-temperature-property (TTP) and the time-temperature-transformation (TTT) curves are both effective approaches to evaluate the quenching sensitivity of aluminum alloys. Fink and Willey first use the TTP curves to investigate the quenching sensitivity of 7075 aluminum alloy [8]. Recently, lots of investigations on quenching sensitivity of some 7xxx aluminum alloys have been reported [9–16]. However, most of the previous research objects are high-Cu containing high strength 7xxx aluminum alloy (AA7050 and AA7055) or middle-Cu containing high strength 7xxx aluminum alloy (AA7085) [9, 17, 18]. The quenching sensitivity of low-Cu
containing high strength 7xxx aluminum alloy (AA7097) has seldom been reported, and also few studies focus on comparing with the quenching sensitivity of these types of 7xxx aluminum alloy via TTP curves.

The purpose of the paper is to quantitatively characterize the quenching sensitivity of AA7097 for optimizing quenching process. In this work, the TTP and the TTT curves of AA7097 are obtained by the interrupted quenching technique. The nose temperature and transformation time, the quenching sensitive zone and the constants $k_2$–$k_5$ of the TTP curve have been identified. In addition, the quenching sensitivity of AA7097 has been compared with AA7050, AA7055 and AA7085, and the effects of alloy composition on quenching sensitivity are illustrated.

2. Materials and methods

The samples size of 4 mm × 15 mm × 15 mm were machined from the AA7097 hot extruded plate (the actual composition is shown in table 1). After solution heat-treated at 470 °C for 1 h, the samples were immediately quenched into a salt bath furnace at a temperature of 200 °C–410 °C (8 temperature points, adjacent temperature interval of 30 °C) and isothermally holding for 2 s, 5 s, 10 s, 30 s, 60 s, 300 s and 1800 s. The transfer time of samples was less than 2 s. Besides, the temperature of salt bath furnace was continuously monitored and maintained at ±3 °C of the required temperature. The samples after isothermal treatment were immediately quenched into room temperature water, and then the single-stage aging (T6) was conducted at 120 °C for 24 h.

The hardness of the as-aged samples was tested by the HV-10B durometer, and the hardness for each condition was obtained average value from five points. The conductivity of as-quenched samples was measured by the D60K metal testing apparatus. The crystal structure of the samples was evaluated by x-ray diffraction (XRD, D/max2550pc) with Cu Kα radiation in the scanning range of 10°–80°. The detailed microstructure in grain interior and grain boundary were observed by the transmission electron microscope (TEM, JEM-2100F). The samples prepared for TEM were mechanically ground to 0.07 mm in thickness, punched into 3 mm in diameter and then twin-jet electropolished in 30% HNO₃ and 70% CH₃OH solution at the temperature of −25 °C. The size of quench-induced precipitates and grain boundary precipitates (GBPs) were calculated by Image J software.

3. Results

3.1. The hardness measurement and TTP curves

As illustrated in figures 1(a) and (b), on the one hand, the hardness of aged alloy decreased with the extension of holding time under the same holding temperature. On the other hand, the decrease rate of hardness was associated with the isothermal holding temperature. The decrease rate of hardness grew faster with the increase of temperature during 200 °C–290 °C, while the decrease rate of hardness slowed down with the increase of temperature during 320 °C–410 °C. It was worth noting that the hardness decreased extremely rapidly at 320 °C. After holding for only 300 s, the hardness significantly decreased from HV195.0 to HV140.4, decreasing by 28.0%. However, when the isothermal holding time was 300 s at 200 °C and 410 °C, the values of hardness were reduced by 7.6% and 3.5%, respectively, which were much smaller than that of 320 °C. Furthermore, the hardness dramatically decreased to HV85.8 (decreasing by 56%) when the isothermal holding time reached 1800 s at 320 °C.

The TTP curve is an effective way to determine the quenching sensitivity of aluminum alloys. It is widely accepted that the TTP curve can be expressed by the following equation [10],

\[
t = -k_1 k_2 \exp \left[ \frac{k_3 k_4^2}{RT (K_4 - T)^2} \right] \exp \left[ \frac{k_5}{RT} \right]
\]

Where $t$ is the critical time required for precipitate a constant amount of solute at a certain temperature; $k_1$ is the natural logarithm of the unconverted fraction, and the TTP curve of the corresponding transformation fraction can be obtained by changing the coefficient; $k_2$ is the constant related to the reciprocal of the nucleation number; $k_3$ is the constant related to the nucleation energy; $k_4$ is the constant related to the solvus temperature; $k_5$ is the constant related to the diffusion activation energy; $R$ is the molar constant of the gas.

| Table 1. The chemical composition of AA7097 (in wt%). |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Zn              | Mg              | Cu              | Zr              | Ti              | Si              | Fe              | Al              |
| 7.99            | 1.98            | 0.98            | 0.11            | 0.035           | 0.003           | 0.034           | Bal.            |

\[\text{Table 1. The chemical composition of AA7097 (in wt%).}\]
The TTP curve of AA7097 was obtained by fitting the isothermal treatment temperature and the time corresponding to 95% of peak hardness with equation (1), and then TTP curves for AA7097 with 99.5%, 90%, 80% of peak hardness were constructed (figure 1(c)). Moreover, the coefficients of TTP curves for AA7097 were determined as shown in table 2. From figure 1(c), it can be inferred that the nose temperature of AA7097 was near 320 °C, and the transformation time at the nose temperature of AA7097 was about 1.2 s when setting the time that the peak hardness dropped to 99.5% as the supersaturated solid solution began to decompose. Besides, the quenching sensitive zone was between 230 °C and 370 °C. In this range of temperature, the hardness decreased sharply with prolonging the isothermal holding time. However, the hardness dropped gently beyond the quenching sensitive zone. For example, the decrease of hardness was less than 10% even after isothermally treating for 1800 s at 200 °C.

### Table 2. The TTP coefficients for AA7097.

| $k_2$/s | $k_3$/J mol$^{-1}$ | $k_4$/K | $k_5$/J mol$^{-1}$ |
|--------|-------------------|---------|-------------------|
| 2.08 $\times$ 10$^{-9}$ | 1554.66 | 807.40 | 103323.12 |

The TTP curve of AA7097 was obtained by fitting the isothermal treatment temperature and the time corresponding to 95% of peak hardness with equation (1), and then TTP curves for AA7097 with 99.5%, 90%, 80% of peak hardness were constructed (figure 1(c)). Moreover, the coefficients of TTP curves for AA7097 were determined as shown in table 2. From figure 1(c), it can be inferred that the nose temperature of AA7097 was near 320 °C, and the transformation time at the nose temperature of AA7097 was about 1.2 s when setting the time that the peak hardness dropped to 99.5% as the supersaturated solid solution began to decompose. Besides, the quenching sensitive zone was between 230 °C and 370 °C. In this range of temperature, the hardness decreased sharply with prolonging the isothermal holding time. However, the hardness dropped gently beyond the quenching sensitive zone. For example, the decrease of hardness was less than 10% even after isothermally treating for 1800 s at 200 °C.

### 3.2. The conductivity measurement and TTT curves

Figures 2(a) and (b) shows the conductivity of the samples after 200 °C–410 °C isothermal treatments. The conductivity of the samples increased with the extension of holding time under the same holding temperature. In addition, it was worth noting that the increase of conductivity grew faster with the increase of temperature during 200 °C–290 °C, while the increase of conductivity slowed down with the increase of temperature during 320 °C–410 °C.

The conductivity is closely related to phase transformation. During the process of quenching, the precipitation of quench induced precipitates results in a decrease in the supersaturation of solid solution. The decrease of supersaturated solid solution causes the lower lattice distortion of the aluminum matrix, and then the effect of hindrance to the conductive electrons becomes smaller. Finally, the mean free path of the
conductive electrons turns higher and the conductivity increases. Therefore, the change in conductivity is used to reflect the volume fraction of the phase transformation of aluminum alloy [16, 19, 20]. It was reported that the phase transformation volume fractions \( \varphi \) of supersaturated solid solution during the isothermally holding process can be expressed by equation (2) [21].

\[
\varphi = \frac{\gamma - \gamma_{\text{min}}}{\gamma_{\text{max}} - \gamma_{\text{min}}}
\]

Where \( \gamma \) is the conductivity of the alloy under different isothermal conditions; \( \gamma_{\text{min}} \) is the conductivity of the alloy when supersaturated solid solution has not begun to decompose, and the corresponding phase transformation volume fraction is 0, herein the conductivity of alloy that directly quenched into room temperature water after solution heat treatment is 32.7% IACS; \( \gamma_{\text{max}} \) is the conductivity of the alloy when the supersaturated solid solution is completely decomposed, and the corresponding phase transformation volume fraction is 100%. Here, the conductivity of alloy after isothermally holding for 48 h at 320 °C is 44.0% IACS.

According to the conductivity data obtained by the experiment (figures 2(a) and (b)), and the \( \varphi \) in different isothermal holding temperature is calculated in terms of equation (2). The TTT curves are shown in figure 2(c). It was demonstrated that the nose temperature was approximately 320 °C. The transformation time at nose temperature was the shortest, and the rapid decomposition and transformation of the supersaturated solid solution at nose temperature resulted in high quenching sensitivity. In contrast, the transformation time was longer at the higher or lower isothermal holding temperature, which indicated that the decomposition rate of the supersaturated solid solution was slower.

3.3. Microstructure

Figure 3 exhibits the precipitates morphology of as-aged alloy in grain interior and grain boundary after isothermally holding for 0 s, 30 s, 300 s and 1800 s at 320 °C. As illustrated in figures 3(a) and (b), the fine precipitates were uniformly distributed in grain interior, and the small size and continuous distribution of grain boundary precipitates (GBPs) were observed after rapidly quenching into room temperature water and aging heat treatment. Figure 4 shows the selected area electron diffraction (SAED) pattern in \( \langle 100 \rangle \) \text{Al} projections of AA7097 alloy (320 °C / 0 s). It was indicated that the \( \eta' \) phase (MgZn2) and Al3Zr phases can be found in AA7097.
(320 °C/0 s). However, coarse rod-shaped quench-induced $\eta$ phase (MgZn$_2$, hexagonal crystal structure, lattice parameter $a = 0.515–0.521$ nm, $c = 0.848–0.869$ nm [22–24]) was nucleated on Al$_3$Zr dispersoids after isothermally holding for 30 s at 320 °C, which was similar to findings from former works [4, 25, 26]. Moreover, the coarse and discontinuous GBPs and the precipitates free zone (PFZ) appeared after isothermally holding for 30 s at 320 °C. With the extension of isothermal holding time, the number and size of quench-induced $\eta$ phase, as well as the width of PFZ gradually increased. However, the size of GBPs remained almost unchanged after isothermally holding for more than 300 s (figure 5). Figure 6 shows the precipitates of AA7097 after isothermally holding for 30 s at temperatures of 230 °C and 410 °C. Compared with 320 °C/ 30 s isothermal treatment, the few quench-induced $\eta$ phases can be observed in grain interior (figures 6(a) and (c)), and the smaller size of GBPs are appeared (figures 6(b) and (d)). Moreover, it was shown that the Al$_3$Zr dispersoids and grain boundary acted as preferential nucleation sites for the coarse equilibrium $\eta$ phase (figure 5). Especially, a small amount of high aspect ratio 'Plate-like' Y phase (it primarily contained with Al, Cu, Zn and Mg elements, and the crystallography
was similar to \( T_1(Al_2CuLi) \) with hexagonal symmetry, lattice parameter \( a = 0.429 \text{ nm}, c = 1.385 \text{ nm} \) \cite{27–29} was showed on the dislocations and the dark ‘Bean-like’ \( Al_3Zr \) dispersoids after 230 °C/30 s isothermal treatment (figure 7).

Figure 8 shows the x-ray diffraction (XRD) pattern of the AA7097 after isothermal holding for different times at 320 °C. The diffraction peak intensity of \( MgZn_2(\eta, \eta') \) around the diffraction angle of 20° and 42° gradually increased with the extension of holding time. It was indicated that the volume of quench-induced precipitates increased with prolonging isothermal holding time, which was consistent with the results of conductivity measurement and microstructural characteristics.

4. Discussion

4.1. Phase transformation kinetics and microstructure evolution

The vertical section phase diagram of AA7097 calculated by Thermo-calc software according to the alloy composition is shown in figure 9. It was indicated that the phase transformation of AA7097 during the solutionizing-quenching process was mainly \( \alpha-Al \rightarrow \alpha-Al + MgZn_2(\eta, \eta') \). Moreover, the TTT curves calculated by JMat-Pro software in terms of the composition of AA7097 are shown in figure 10. The quench-induced precipitates of AA7097 were mainly \( \eta \) and \( \eta' \) phase. It was also showed that the nose temperature of \( \eta' \) phase was about 320 °C while the nose temperature of the \( \eta \) phase was higher. The results were consistent with the previous microstructure observations (figures 3 and 6). Besides, the quench-induced Y phase of 7xxx series aluminum alloys was discovered in recent years \cite{27–29}, which was preferentially precipitated on dislocations \cite{29}. The Y phase was presented at the quenching cooling rate within 3.2 k s\(^{-1}\) and less than 300 k s\(^{-1}\) of AA7085.
and AA7150, respectively [4]. Interestingly, in this work, the Y phase also appeared after 230 °C/30 s isothermal treatment for AA7097.

The transformation kinetics of quench-induced precipitates was usually fitted by Johnson-Mehl-Avrami equation [30], which was expressed as follows:

\[ \varphi = 1 - \exp(-kt^n) \]

Where \( \varphi \) is the phase transformation volume fraction (calculating in section 3.1); \( t \) is the reaction time; \( k \) is the Avrami constant related to nucleation and growth rate; \( n \) is the Avrami exponent which reflects the phase transformation process.

The \( k \) and \( n \) are shown in table 3, which were obtained by fitting time (t)-phase transformation volume fraction (\( \varphi \)) curve. The isothermal transformation 'S' curve of the nose temperature (320 °C) fitted by Johnson-Mehl-Avrami equation is shown in figure 11. It was reported that the large value of \( k \) was associated with rapid transformation velocity [31]. Consequently, the largest value of \( k \) (\( k = 0.03398 \)) indicated the fastest rate of phase transformation and the highest quenching sensitivity at 320 °C, which were consistent with the results observed from TTT and TTP curves (figures 1(c) and 2(c)). Moreover, the nose temperature of \( \eta' \) phase was about 320 °C, and the nose temperature of the \( \eta \) phase was higher than that of \( \eta' \) phase according to the results.

Figure 6. TEM images of aged alloy after holding 30 s at temperatures of 230 °C (a), (b) and 410 °C (c), (d).

Figure 7. TEM micrographs of the aged specimens after isothermally holding for 30 s at 230 °C: (a) 'Bean-like' Al\(_3\)Zr; (b) 'Plate-like' Y phase.
calculated by JMatPro software (figure 10). It was further verified the accuracy of $k$. From 200 °C to 410 °C, the value of $k$ first increased and then decreased, which indicated that the rate of phase transformation first grew faster and then slowed down. In addition, the value of $n$ was between 0.5 and 1. For the phase transformation process controlled by long-range diffusion, when $n = 1$, it indicated plates or needles; when $n = 0.5$, it indicated large plates [32]. In this work, the value of $n$ was between 0.5 and 1, which indicated that the phase transformation was dominated by rod-like and plate-like precipitates (as shown in figures 3, 6 and 7).

In order to better understand the phase transformation process during the quenching process of the alloy, the schematic of the microstructure evolution of AA7097 during isothermally holding at 320 °C is drawn in figure 12. For grain interior, Al$_3$Zr dispersoids can act as preferential nucleation sites due to high interfacial energy between dispersoids and Al matrix during the slow quenching process. Consequently, the more quench-induced precipitates nucleated at Al$_3$Zr dispersoids. And the size of quench-induced precipitates increased with the increase of isothermal holding time. Meanwhile, the larger GBPs and the wider PFZ appeared, and the distribution of GBPs transformed from continuous to discontinuous with the increase of isothermal holding time.

![Figure 8. X-ray diffraction pattern of the AA7097 after isothermally holding for different times at 320 °C.](image)

![Figure 9. Vertical section phase diagram based on the AA7097 composition.](image)
4.2. Comparison of the quenching sensitivity for several 7xxx aluminum alloys

Figure 13 and table 4 show the comparison of the quenching sensitivity for several 7xxx aluminum alloys in terms of the TTP curves. It can be inferred that the quenching sensitivity of AA7055 was the highest. Moreover, the quenching sensitivity of AA7097 was lower than that of AA7050 but higher than that of AA7085, which indicated that AA7097 can be used as the high strength, thick section and large size of aircraft component.

Figure 14 shows the relationship between alloy composition and transformation time at nose temperature. The alloy composition was an important factor affecting the quenching sensitivity of 7xxx aluminum alloys. The Zn, Mg and Cu atoms dissolved in the Al matrix can lead to different degrees of lattice distortion, while Cu atom caused more distortion to the Al matrix lattice and resulted in higher distortion energy relative to Zn and Mg atoms. The location with higher distortion energy can easily become heterogeneous nucleation sites of the equilibrium phase and then promote the generation of the equilibrium phase. Consequently, the total (Zn + Mg + Cu) content and the Cu content were two key factors that affected the quenching sensitivity of

### Table 3. The values of \( k' \) and \( n' \) obtained by Johnson-Mehl-Avrami equation fitted at different isothermal holding temperatures.

| Temperature/°C | 200    | 230    | 260    | 290    | 320    | 350    | 380    | 410    |
|----------------|--------|--------|--------|--------|--------|--------|--------|--------|
| \( k \)        | 0.00148| 0.00298| 0.00766| 0.01649| 0.03398| 0.01930| 0.01217| 0.00872|
| \( n \)        | 0.88582| 0.82677| 0.71838| 0.66697| 0.54849| 0.35530| 0.51479| 0.50886|

4.2. Comparison of the quenching sensitivity for several 7xxx aluminum alloys

Figure 13 and table 4 show the comparison of the quenching sensitivity for several 7xxx aluminum alloys in terms of the TTP curves. It can be inferred that the quenching sensitivity of AA7055 was the highest. Moreover, the quenching sensitivity of AA7097 was lower than that of AA7050 but higher than that of AA7085, which indicated that AA7097 can be used as the high strength, thick section and large size of aircraft component.

Figure 14 shows the relationship between alloy composition and transformation time at nose temperature. The alloy composition was an important factor affecting the quenching sensitivity of 7xxx aluminum alloys. The Zn, Mg and Cu atoms dissolved in the Al matrix can lead to different degrees of lattice distortion, while Cu atom caused more distortion to the Al matrix lattice and resulted in higher distortion energy relative to Zn and Mg atoms. The location with higher distortion energy can easily become heterogeneous nucleation sites of the equilibrium phase and then promote the generation of the equilibrium phase. Consequently, the total (Zn + Mg + Cu) content and the Cu content were two key factors that affected the quenching sensitivity of
Al–Zn–Mg–Cu alloy \([33, 34]\). It was also reported that the influence of each element on the quenching sensitivity of alloy from high to low is Cu, Mg and Zn \([35]\). Therefore, the highest quenching sensitivity of AA7055 compared with the other alloys was attributed to the highest Cu content and total \((Zn + Mg + Cu)\) content. In addition, the total \((Zn + Mg + Cu)\) content of AA7097 and AA7050 was similar, but the Cu content of AA7050 was much higher than that of AA7097. It resulted in the higher quenching sensitivity of AA7050 compared with AA7097. However, the total \((Zn + Mg + Cu)\) content of AA7097 was higher than that of AA7085, which contributed to higher quenching sensitivity of AA7097 compared with AA7085.

**Figure 12.** The schematic microstructure evolution of AA7097 during isothermally holding at 320 °C.

**Figure 13.** Comparison of the quenching sensitivity for several 7xxx aluminum alloys.

**Table 4.** The \(k_2\)–\(k_5\) coefficients, nose temperature and corresponding transformation time at nose temperature for TTP curves of AA7097 and other typical 7xxx aluminum alloys.

| Alloy    | \(k_2/s\) | \(k_3/(J \text{ mol}^{-1})\) | \(k_4/K\) | \(k_5/(J \text{ mol}^{-1})\) | Nose temperature (°C) | Transformation time at nose temperature (s) | References |
|----------|-----------|-------------------------------|-----------|-------------------------------|-----------------------|------------------------------------------|-----------|
| 7097-T6  | 2.1E-9    | 1555                          | 807       | 1.03E5                        | 320                   | 1.20                                     | This work |
| 7085-T6  | 1.1E-17   | 4410                          | 816       | 1.69E5                        | 290                   | 4.50                                     | [17]      |
| 7050-T6  | 1.8E-17   | 4620                          | 874       | 1.66E5                        | 330                   | 0.31                                     | [18]      |
| 7055-T6  | 2.1E-11   | 1061                          | 802       | 1.23E5                        | 355                   | 0.15                                     | [9]       |

Al–Zn–Mg–Cu alloy \([33, 34]\). It was also reported that the influence of each element on the quenching sensitivity of alloy from high to low is Cu, Mg and Zn \([35]\). Therefore, the highest quenching sensitivity of AA7055 compared with the other alloys was attributed to the highest Cu content and total \((Zn + Mg + Cu)\) content. In addition, the total \((Zn + Mg + Cu)\) content of AA7097 and AA7050 was similar, but the Cu content of AA7050 was much higher than that of AA7097. It resulted in the higher quenching sensitivity of AA7050 compared with AA7097. However, the total \((Zn + Mg + Cu)\) content of AA7097 was higher than that of AA7085, which contributed to higher quenching sensitivity of AA7097 compared with AA7085.
Figure 14. The relationship between alloy composition and transformation time at nose temperature.

Figure 15. Vertical section phase diagram based on the four alloy composition with variable Cu values: (a) AA7097; (b) AA7085; (c) AA7050; (d) AA7055.
The vertical section phase diagram based on the four alloy composition with variable Cu values calculated by Thermo-calc software is shown in figure 15, which indicated that the lowest temperature limits of the $\alpha$-Al region of AA7097, AA7085, AA7050 and AA7055 were 450 °C, 450 °C, 485 °C and 480 °C, respectively. When the temperature drops to 450 °C, the $\alpha$-Al phase of AA7050 and AA7055 will gradually transform into the $\alpha$-Al + $\alpha$-Al,$\alpha$-Al + $\alpha$-Al,$\alpha$-Al + $\alpha$-Al,$\alpha$-Al CuMg phase, while the $\alpha$-Al phase of AA7097 and AA7085 remains stable and does not decompose, which contributes to the low quenching sensitivity of AA7097 and AA7085. In addition, figure 16 shows the vertical section phase diagrams with same Zn and same temperature (470 °C) of four alloys. It can be observed that the composition range of AA7097 and AA7085 are completely within the $\alpha$-Al phase region at the temperature of 470 °C. However, the composition range of AA7050 and AA7055 is mostly located in the area of $\alpha$-Al + $\alpha$-Al CuMg at 470 °C. The coarse $\alpha$-Al CuMg phase can act as heterogeneous nucleation sites during the quenching process, which also responsible for the higher quenching sensitivity of AA7050 and AA7055 compared with AA7097 and AA7085.

5. Conclusions

1. The quenching sensitive zone of AA7097 is 230 °C–370 °C. The nose temperature and the transformation time are about 320 °C and 1.2 s, respectively.
2. The phase transformation kinetics of AA7097 during isothermal treatment has been established according to TTT curves and microstructural analysis.

3. The quenching sensitivity of AA7097 is lower than that of AA7055 and AA7050, but higher than that of AA7085.

Acknowledgments

The authors also acknowledge the financial support of National Key Research and Development Program of China (No. 2016YFB0300801), State Key Laboratory of High Performance Complex Manufacturing of Central South University (No. ZZYJKT2017-02), Natural Science Foundation of Hunan Province of China (No. 2018J3645).

ORCID iDs

Kanghua Chen @ https://orcid.org/0000-0002-1139-8304

References

[1] Marlaud T, Deschamp A, Bley F, Lefebvre W and Baroux B 2010 Evolution of precipitate microstructures during the retrogression and re-ageing heat treatment of an Al–Zn–Mg–Cu alloy Acta Mater. 58 4814–26
[2] Azarniya A, Taheri A K and Taheri K K 2019 Recent advances in ageing of Txxx series aluminum alloys: a physical metallurgy perspective J. Alloy. Compd. 781 945–83
[3] AMS 4365 2017 Aluminum alloy, plate, 7.9Zn–1.2Cu–2.1Mg–0.10Zr (7097–T7651) solution heat treated, stress relieved, and overaged SAE International
[4] Liu S, Li Q, Lin H, Sun L, Long T, Ye L and Deng Y 2017 Effect of quenching-induced precipitation on microstructure and mechanical properties of 7085 aluminum alloy Mater. Des. 132 119–28
[5] Robinson J S, Tanner D A, Potegem S V and Evans A 2012 Influence of quenching and aging on residual stress in Al–Zn–Mg–Cu alloy 7449 Mater. Sci. Tech. 28 420–30
[6] Sun Y, Jiang F, Zhang H, Su J and Yuan W 2016 Residual stress relief in Al–Zn–Mg–Cu alloy by a new multistage interrupted artificial aging treatment Mater. Des. 92 281–7
[7] Bates C E and Totten G E 1988 Procedure for quenching media selection to maximize tensile properties and minimize distortion in aluminum alloy parts Heat Treat. Met. 4 89–97
[8] Fink W L and Willey L A 1948 Quenching of 75S aluminum alloy AIPMPE 175 414–27
[9] Liu S, Zhong Q, Zhang Y, Liu W, Zhang X and Deng Y 2010 Investigation of quench sensitivity of high strength Al–Zn–Mg–Cu alloys by time-temperature-properties diagrams Mater. Des. 31 3116–20
[10] Robinson J S, Cudd R L, Tanner D A and Dolan G P 2001 Quench sensitivity and tensile property inhomogeneity in 7010 forgings J Mater Process Tech. 119 261–7
[11] Xie H, Xiao Z, Li Z, Wang M, Ma S and Jiang H 2019 Quench sensitivity of AA7N01 alloy used for high-speed train body structure JOM 71 1681–6
[12] Ye J, Pan Q, Li H, Huang Z, Liu Y, Wang X and Li M 2019 Quenching sensitivity of a 7A46 aluminum alloy JOM 71 2054–62
[13] Li S, Dong H, Wang X and Liu Z 2019 Quenching sensitivity of Al–Zn–Mg alloy after non-isothermal heat treatment Materials 12
[14] Lin L, Liu Z, Bai S, Zhou Y, Liu W and Lv Q 2017 Effects of Ge and Ag additions on quench sensitivity and mechanical properties of an Al–Zn–Mg–Cu alloy Mater. Sci. Eng. A 682 640–7
[15] Nie B, Liu P and Zhou T 2016 Effect of compositions on the quenching sensitivity of 7050 and 7085 alloys Mater. Sci. Eng. A 667 106–14
[16] Wu S, Yi Y, Huang S, Li J and Li C 2016 Research on quench sensitivity and microstructure analysis of 7050 aluminum alloy Acta. Metall. Sin. 52 1503–9
[17] Xiong B Q, Li X W, Zhang Y A, Li Z H, Zhu B H, Wang F and Liu H W 2011 Quench sensitivity of Al–Zn–Mg–Cu alloys Trans. Nonferrous Met. Soc. China 21 2631–8
[18] Liu W J 2011 The research about the quench induced precipitation and quenching sensitivity of Al–Zn–Mg–Cu alloys PhD Thesis Central South University
[19] Liu M, Zhang Z, Bertron F and Chen X G 2019 Investigation of the quench sensitivity of an AlSi10Mg alloy in permanent mold and high-pressure vacuum die castings Materials 12 1–13
[20] Dai X, Xiong C, Li N and Luo Y 2019 TTT and TTP diagrams of quenching sensitivity of Al-9.0Zn-2.5Mg-1.5Cu-0.15Zr-0.25Sc alloy Rare. Metal. Mat. Eng. 48 0721–7
[21] Chen L and Yu Y 2011 Phase Transformations in Metals and Alloys (Beijing: Higher Education Press)
[22] Friauf J 1927 The crystal structure of magnesiun di-zincide Phys. Rev. 29 34
[23] Komura Y and Tokunaga K 1980 Structural studies of stacking variants in Mg-base Friauf-Laves phases Acta Cryst. B 36 1548
[24] Li C Q, Zeng S M, Chen Z Q, Cheng N P and Chen T X 2014 First-principles calculations of elastic and thermodynamic properties of the four main intermetallic phases in Al–Zn–Mg–Cu alloys Comp. Mater. Sci. 93 210–20
[25] Li C B, Wang S L, Zhang D Z, Liu S D, Shan Z J and Zhang X M 2016 Effect of Zener-Hollomon parameter on quench sensitivity of 7085 aluminum alloy J. Alloys Compd. 688 456–62
[26] Liu S D, Zhang X M, Chen M A and You J H 2008 Influence of aging on quench sensitivity effect of 7055 aluminum alloy Mater. Charact. 59 53–60
[27] Starink M J, Milkereit B, Zhang Y and Rometsch P A 2015 Predicting the quench sensitivity of Al–Zn–Mg–Cu alloys: a model for linear cooling and strengthening Mater. Des. 88 958–71
[28] Yang B, Milkereit B, Zhang Y, Rometsch P A, Kessler O and Schick C 2016 Continuous cooling precipitation diagram of aluminum alloy AA7150 based on a new fast scanning calorimetry and interrupted quenching method Mater. Charact. 120 50–7
[29] Zhang Y, Weyland M, Milkereit B, Reich M and Rometsch P A 2016 Precipitation of a new platelet phase during the quenching of an Al–Zn–Mg–Cu alloy Sci. Rep. 6
[30] Staley J T 1987 Quench factor analysis of aluminium alloys Mater. Sci. Tech. 3 923–35
[31] Porter D A and Easterling K E 1992 Phase Transformations in Metals and Alloys (London: Chapman & Hall Press) pp 263–381
[32] Christian J W 2002 The theory of Transformations in Metals and Alloys, Part I. (Oxford: Pergamon) pp 546
[33] Zhang Z H, Xiong B Q, Zhu B H and Zuo Y T 2014 Stability of supersaturated solid solution of quenched Al–X (X = Zn, Mg, Cu) binary alloys Rare Met. 33 139–43
[34] Lim S T, Yun S J and Nam S W 2004 Improved quench sensitivity in modified aluminum alloy 7175 for thick forging applications Mater. Sci. Eng. A 371 82–90
[35] Bryant A J 1966 The effect of composition upon the quench-sensitivity of some Al–Zn–Mg alloy J. Inst. Metals. 94 94–9