Proceedings of the 12th International Conference on
Aluminium Alloys, September 5-9, 2010, Yokohama, Japan

pp. 2147-2151

Effect of Heating-rate on the Thermal-mechanical Behavior of Pre-loaded Aluminium Alloy 6061-T6

Bin Chen[1, 2], Quan Yuan[1] and Ji Luo[1]

[1]College of Resources and Environmental Science, Chongqing University, Chongqing 400044, China

[2] Key Laboratory for the Exploitation of Southwest Resources and Environmental Disaster Control Engineering, Ministry of Education, Chongqing University, Chongqing 400044, China

The response and failure of the specimens of aluminium alloy 6061-T6 subjected to different pre-loaded stress levels and heating rates were investigated with a Gleeble-1500 thermal-mechanical material testing system. It was found that the increases of either pre-loaded stresses or heating-rates decrease the failure temperatures of the specimens. The metallographs of the tested specimens were also observed. It showed that the high heating-rate may cause stronger local thermal inconsistency, which remarkably increases the microdefects in the material and reduce the macroscopic mechanical properties of the material.

Keywords: *Aluminium alloy 6061-T6; pre-loaded stress; heating rate; failure temperature; local thermal inconsistency.*

1. Introduction

It is known that the high and rapid heating temperature may result in a remarkable change of the microstructures of materials [1-3]. The microstructural change may change the mechanical properties of materials. The investigation on the changes of the microstructures and the mechanical properties of materials at high and rapid heating temperature may help to avoid material failure at high and rapid heating temperature and provide available information for making use of fast-heating technology [4-6].

The failure of materials and structures caused by the high and rapid heating temperature is receiving increasing attention [7-10]. Liu et al [9] investigated the nonlinear softening of aluminium alloy subjected to fast heating. It was found that the differences in heating-rate history may cause differences in both the grain size and the macroscopic mechanical properties of the material, which was accounted for the dynamics of recrystallization. Wang et al [10] conducted a set of tensile test of low-alloy steel 30CrMnSi subjected to fast heating histories with different heating-rates. The test results showed distinct differences in both the rupture strength and the metallograph of the material. Peng et al [11-14] investigated the effect of heating-rate on the mechanical properties of aluminium alloy LY12 and indicated that the material experiencing higher heating-rate histories possesses lower rupture strength and that the pre-stressed material fails at lower temperature, which was attributed to the increase of microdefects due to the strong local thermal inconsistency at high heating-rate. In this paper, a systematic experiment was conducted with a Gleeble-1500 thermal-mechanical material testing system to investigate the effect of heating-rate on the failure temperature of the specimens of pre-loaded aluminium alloy 6061-T6. The metallographs of the tested material were also observed and analyzed. This work is significant for understanding the failure mechanism of aluminium alloy under high heating-rate and well making use of aluminium alloy.

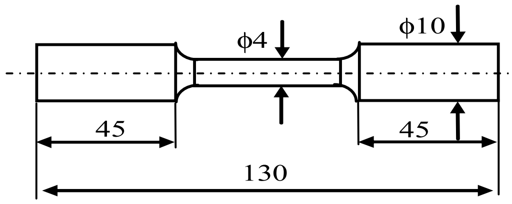


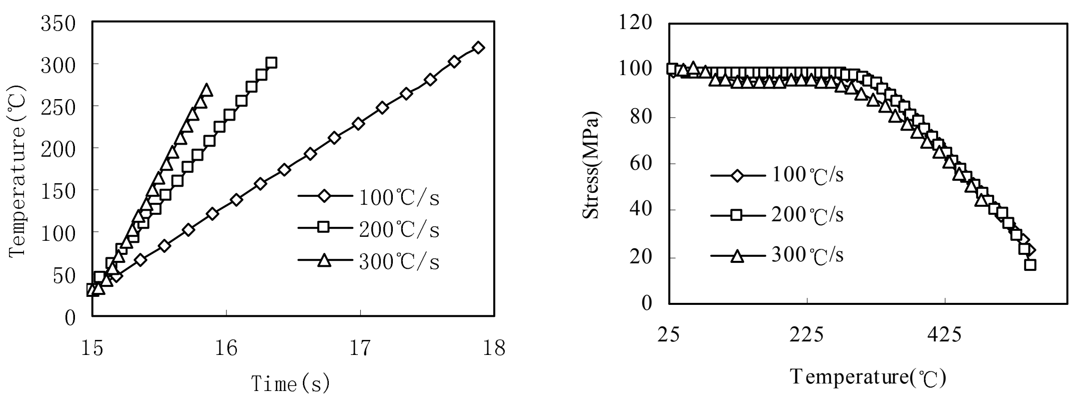
Fig. 1 Draft of specimen (mm)

2. Experimental method

A Gleeble-1500 thermal-mechanical material testing system was used to investigate the effect of heating-rate on the failure temperature of the specimens of pre-loaded aluminium alloy 6061-T6 (Fig. 1). In the experiment, the specimens were heated with direct current by applying an electrical voltage directly between the two ends of the specimens. The experimental temperature and its rate were measured with a chromel-alumel thermocouple welded directly on the surface of the working section and controlled by a computer [14, 15]. The tensile traction and the temperature were recorded synchronously with the data acquisition element of the testing system, respectively. To investigate the effect of heating-rate on the failure temperature of aluminium alloy specimens, three different levels of pre-loaded stresses, 100, 200 and 300 MPa, were prescribed, for each of which three different heating-rates, 100, 200 and 300℃/s, were assigned. Namely, the specimens of the aluminium alloy were firstly preloaded to a prescribed stress level, and then they are heated with one of the three prescribed heating-rates. In order to make clear the effect mechanisms of the heating-rates on the mechanical properties of the pre-loaded aluminium alloy, the metallographs of the tested specimens were observed and analyzed. The samples used for the metallographic observation were cut from the vicinity of the fracture section of tested specimens, eroded in a mixed 2.5%HNO_3, 1.5%HCl and 1%HF solution for 10-20s, and then cleaned for observation.

3. Results and discussions

Fig. 2 (a) shows the measured relationship between the temperature and time of the specimens of the pre-loaded aluminium alloy 6061-T6. It can be seen from Fig. 2 (a) that the temperature increases almost linearly at different heating-rates, which shows that the heating-rates are reliably given and controlled. Fig. 2 (b) indicates the measured relationship between the stress and temperature of the specimens subjected the pre-loaded stress 100MPa and heated with three different heating-rates 100, 200 and 300℃/s, respectively. It can be found from Fig. 2 (b) that the prescribed pre-loaded stress σ_b =100MPa is transitorily maintained before the failure temperature is reached, and then falls rapidly. It can also be observed that the failure temperature of the pre-loaded material reduces with the increase of the heating rates. Fig. 3 (a) shows the measured relationship between the temperature and time of the specimens. It can also be seen from Fig. 3 (a) that the temperature also increases almost linearly at different heating-rates, which shows that the heating-rates are also reliably given and controlled. Fig. 3 (b) reveals the measured relationship between the stress and temperature of the specimens subjected the pre-loaded stress 200MPa and heated with three different heating-rates, 100, 200 and 300℃/s. It

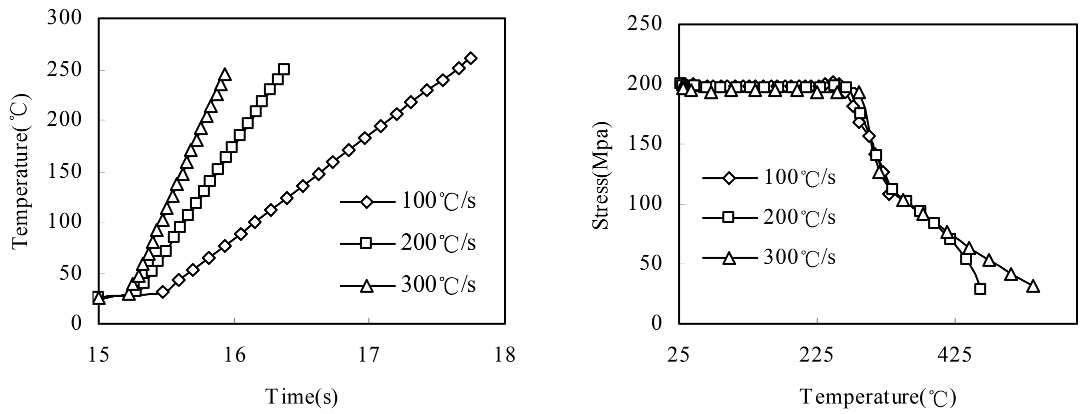


(a) (b)

(a) Temperature vs. time; (b) Stress vs. temperature

Fig. 2 Testing results at different heating rates (with σ_b=100MPa) can also be found from Fig. 3 (b) that the prescribed pre-loaded stress σ_b =200MPa also transitorily maintains until the failure temperature is reached. It can also be observed that the failure temperature of the pre-loaded material also reduces with the increase of the heating rates. Fig. 4 (a) shows the variation of the failure temperatures against the pre-loaded stresses, taking the heating-rate as a parameter. It can be seen that, for a fixed heating-rate, the failure temperature of the pre-loaded material reduces with the increase of the pre-loaded stress, due to the softening of the material at an elevated temperature. The variation of the failure temperature against the heating-rate at different pre-loaded stresses is shown in Fig. 4 (b). Remarkable reduction in the failure temperature can be observed with the increase of the heating-rate, which implies that the heating-rate may play a significant role in the failure of the pre-loaded materials.

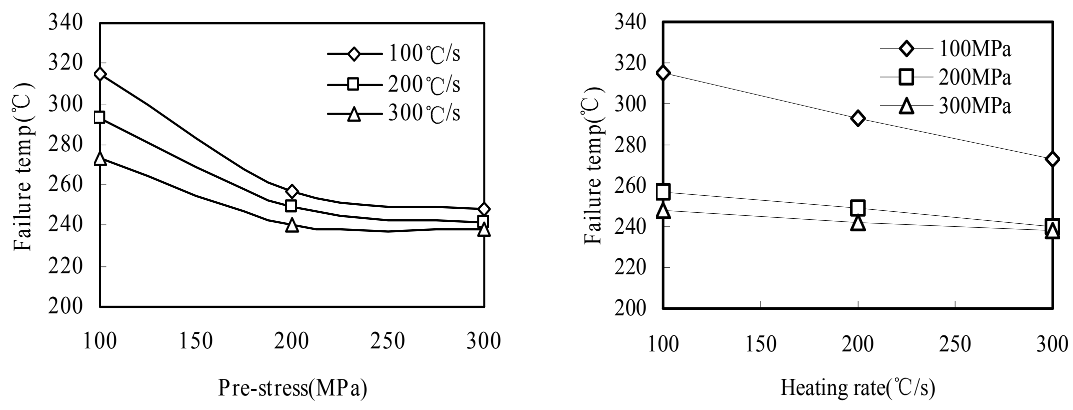
Fig. 5(a)-(c) shows the metallographs of the specimens subjected to the pre-loaded stresses σ_b =100MPa and the heating-rates of 100, 200 and 300℃/s, respectively. It can be seen from Fig. 5 (a)-(c) that there are fewer microvoids in the specimen at a lower heating-rate, and the microvoids will develop in both the size and density with the increase of the heating-rate. Fig. 6(a)-(c) show the metallographs of the specimens subjected to the pre-loaded stresses σ_b=200MPa and the heating-rates of 100, 200 and 300℃/s, respectively. It can also be seen from Fig. 6 (a)-(c) that the microvoids in the specimen increase in both the size and density with the increase of the heating rates. Fig. 7 (a)-(c) show the metallographs of the specimens subjected to the pre-loaded stresses σ_b=300MPa and the



(a) (b)

(a) Temperature vs. time; (b) Stress vs. temperature

Fig.3 Testing results at different heating rates (with σ_b=200MPa)



(a) (b)

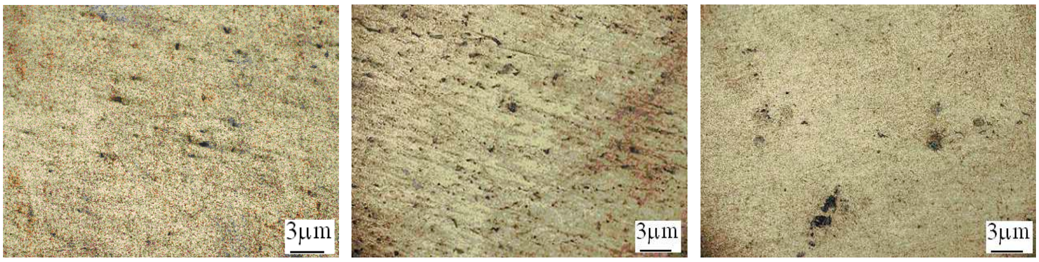
(a) Failure temperature vs. pre-stress; (b) Failure temperature vs. heating rates

Fig.4 Failure temperatures at different pre-stresses and heating-rates heating-rates of 100, 200 and 300℃/s, respectively. It can also be seen from Fig. 7 (a)-(c) that the microvoids in the specimen increase in both the size and density with the increase of the heating rates. Connecting the mechanical behavior of the material under the different pre-loaded stresses heating-rates, it can be speculated that the increase of the heating-rates brings the increase of the microvoids, and then the increase of the microvoids induces the reduction of the failure temperature. The comparisons between the metallographs of the material, subjected to the identical heating-rates but the different pre-loaded stresses, σ_b =100, 200 and 300 MPa (Fig. 5-Fig. 7), shows that the microvoids in the material also increase with the increase of the pre-load stress, which also induce the reduction of the failure temperature.

The changes of the microstructures and the mechanical properties of the pre-loaded material at the high heating-rates can be attributed to the local thermal inconsistency in the material [14, 15]. The local thermal inconsistency may bring larger local residual stress and higher local temperature, in turn, expedites the nucleation, growth and coalescence of the microvoids or microcracks in the material. The grown microvoids or microcrackles may markedly degrade the mechanical properties of the material and make the material fails even at a relatively low level of pre-loaded stress.

(a) (b) (c)

Fig. 5 Metallographs at pre-stress σ_b =100MPa and different heating rates: (a)100; (b)200; (c)300℃/s



(a) (b) (c)

Fig. 6 Metallographs at pre-stress σ_b =200MPa and different heating rates: (a)100; (b)200; (c)300℃/s

(a) (b) (c)

Fig. 7 Metallographs at pre-stress of σ_b =300MPa and different heating rates: (a)100; (b)200; (c)300℃/s

4. Conclusions

Using a Gleeble-1500 thermal-mechanical testing system, a set of experiments was conducted to investigate the dependence of the failure temperature of the specimens of the pre-loaded aluminium alloy 6061-T6 on the heating-rate and pre-load stress. The metallographs of the tested material were also analyzed to investigate the mechanism of the heating-rate effect on the mechanical behavior of the pre-loaded material. Following conclusions were obtained: (1) The increases of pre-load stress will decrease the failure temperature of the material. (2) The increases of heating-rate will also decrease the failure temperature. (3) The high heating-rate may cause stronger local thermal inconsistency, which will remarkably increase microvoids in the material, and then degrade the macroscopic mechanical properties of the material.

Acknowledgement

The authors gratefully acknowledge the financial support to this work from the Natural Science Foundation of China (Grant no. 10872221).

References

[1] M. Han, Z. Liu and Y. Liu: Explosion and Impact 19 (1999) 20–26.
[2] Y. Chen, G. Li and J. Zhang: High Power Laser and Particle Bea. 7 (1995) 245–251.
[3] M. Sumida: J. Alloys Comp. 460 (2008) 619-626.
[4] P. B. Srinivasan and J. Liang: Applied Surface Sci. 255 (2009) 4212-4218.
[5] Y. He and H. Fu: Script Mater. 58 (2008) 504-507.
[6] H. Chen: High Pow. Laser Part. Beam. 4 (1992) 141-147.
[7] Z. X. Wang and X. F. Liu: Acta Metal. Sini. 44 (2008) 1378-1383.
[8] Y. Lin and H. G. Yan: Mater. Mech. Eng. 30 (2006) 38-42.
[9] Z. Liu, M. Han, C. Sun and R. Wang: Acta Metal. Sini. 31 (1995) 229-335.
[10] C. Wang, C. Hung, Y. Sun and Z. Duan: Acta Metal. Sini. 31 (1995) 475–478.
[11] X. Peng, J. Fan, Y. Yan, Y. Chen and Y. Yin: Int. J. Sol. Stru. 40 (2003) 7385-7397.
[12] X. Peng, Y. Qin and X. Zhang: J. Mater. Pro. Tech. 167 (2005) 244-250.
[13] X. Peng, Y. Yang, Y. Chen and Y. Yin: Acta Mech. Soli. Sini. 26 (2005): 72-76.
[14] X. Peng, X. Zhang, J. Fan and B. Chen. Int. J. Sol. Stru. 43 (2006) 3527-3541.
[15] Y. Yang, X. Peng, Y. Chen, Y. Yin and G. Chen: Acta Metal. Sini. 36 (2000) 926-930.