Tensile Deformation Behavior of a Nickel-base Superalloy under Dynamic Loads

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Abstract The tensile deformation behavior of a nickel-base superalloy under the dynamic loads was investigated the by the optical microscope, scanning electron microscope and transmission electron microscope. The results shown that the yield strength of the alloy increases with the increasing of strain rate, eapacily at the strain rate higher than $10^1\ s^{-1}$. While with the increasing of strain rate, the fracture elongation decreases at first, then increases rapidly and shows a minimum value at the strain rate of $10^2\ s^{-1}$. The manner in which the dislocations go through the strengthening phases may be different during the plastic deformation at different strain rates and it is the main reason of the appearance of inflection point in the change of the strength with the strain rate. The obvious increasing of plasticity of the alloy at high strain rate is depended on the deformation twining during the plastic deformation.

Keywords Superalloy, Dynamic load, Deformation behavior, Dislocation

1. Introduction

Superalloy is a kind of important metallic material for engines in the aerospace industry, which is the key point for determination of the thrust and thrust-weight ratio of advanced engines [1-3]. With the rapid developing aerospace industry, the working condition of the superalloy is becoming more and more severe. In traditional aeroengine manufacturing industry, the mechanical properties and deformation behavior of superalloy used for rotating parts under the actual dynamic load is not given full considerations during its designing of structure, composition and microstructure, which is significantly different compared with that under the static load [4-6]. In fact, the Young's modulus, strength, plasticity and ductility will change with the increasing of strain rate [7-10]. Therefore, the study on the deformation behavior of the alloy under the dynamic load is important for the safety of rotating parts used under the service conditions.

The aim of present study is to investigate the strain rate effects on the tensile deformation behavior of a precipitation strengthened nickel-base superalloy used for aero-engine combustor under dynamic loads. And the mechanism for strain-dependence on strength and ductility of the alloy was also discussed.

2. Experimental Procedures

The chemical compositions (wt%) of the alloy are of 0.038 C, 19.970 Cr, 9.990 W, 5.120 Mo, 2.180 Al, 1.290 Ti, 0.020 Mn, 0.080 Si, and balance Ni. The alloy was double vacuum melted, then forged and hot rolled into plates with the thickness of 1 mm After solution treated at 1150 ℃ for 15 min, the alloy was long-term aged at 800 ℃ for 0 h, 100 h, 200 h, 500 h and 1000 h, respectively. The tensile tests of the alloy were performed at room temperature using MTS 810 testing machine and Zwick HTM 5020 high speed tensile testing machine at a strain rates range of $10^{-3}\ S^{-1}$ to $10^3\ S^{-1}$. The resistance strain gage was setupped on the specimens for synchronous collection of the strains and loads during the dynamic deformation with a sampling frequency of 1 MHz. The microstructure evolution, grain size and the tensile fracture surfaces of the tensile specimen were examined using an optical microscope (OLYMPUS GX71), laser scanning confocal microscope (OLYMPUS OLS 3100) and field emission scanning electron microscope (JEOL 7001). The dislocation configuration near the fracture surface was examined by a transmission electron microscope (TECNAI G^2).

3. Results and Discussion

3.1 Strain rate effect on tensile property

Figure 1 shows tensile properties of the alloy aged with different parameters at various strain rates. It shows a similar strain-rate dependence on yield strength: shallow at the strain rates lower than10^1 s^{-1}, and even steeper with increasing of strain rate, especially when the strain rate is higher than 10^2 s^{-1}. It indicates that the plastic deformation mechanism of the alloy begins to change when the strain rate is higher than 10^1 s^{-1}.

The ductility of an alloy aged for different time also shows variation with the increasing of tensile strain rates, as shown in Fig.1b. When the strain rate is increased from 10^{-3} s^{-1} to 10^2 s^{-1}, the fracture elongation decrease obviously, while, then the fracture elongation increased significantly. From the results, it can be concluded that the plastic deformation mechanism of the alloy changed at the strain rate of 10^2 s^{-1}. When the alloy aged with different aging parameters, the increasing of ductility in the alloy aged for 500 h and 1000 h is less than that for 100 h and 200 h.

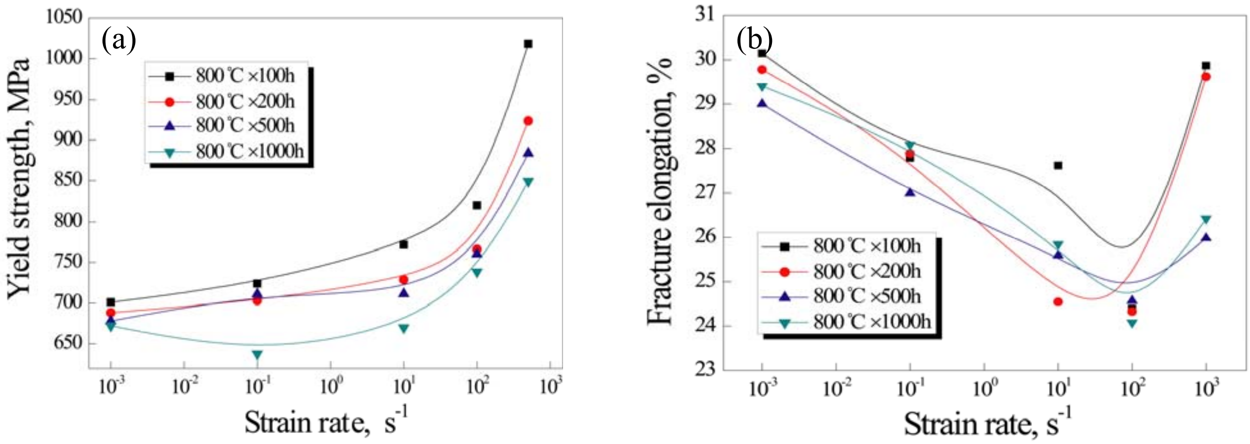

Figure 1. Variation of mechanical properties with the tensile strain rate of the alloy aged by different parameters: (a) yield strength, (b) fracture elongation

3.2 Strain rate effect on tensile fracture morphology

Figure 2 shows the morphologies in fibrous zones of tensile fracture surface of the alloy by aged for 100 h and 100 h with different strain rates. The alloys aged for 100 h and 1000 h exhibit mixed fracture characteristics with ductile and intergranular when the strain rate is lower than 10^{-3} s^{-1}. The small changes can be observed from the fracture morphologies of the alloy with different aging time when the strain rates are increased to 10^3 s^{-1}. It can be found that the percentage of ductile fracture region decreases obviously in the alloy aged for 1000 h as compared with that aged for 100 h at the same strain rate. In addition, the percentage of ductile fracture region in the alloy aged for 1000 h further decreases with the increasing of strain rate and the intergranular fracture characteristics is more apparent.

3.3 Dislocation configurations near fracture surface

Dislocation configurations near the fracture surface in the alloy aged for 200 h at various strain rates are shown in Figure 3. It can be noticed that the dislocation density is not high and it seems no remarkable change with the strain rate of 10^{-3} s^{-1} to 10^1 s^{-1}, while when the strain rate is increased to 10^2 s^{-1}, the dislocation density significantly increases and activation of slip systems can be found with TEM observation. However, when the strain rate is higher than 10^2 s^{-1}, the dislocation density remains stable but dislocation tangles become more severe.

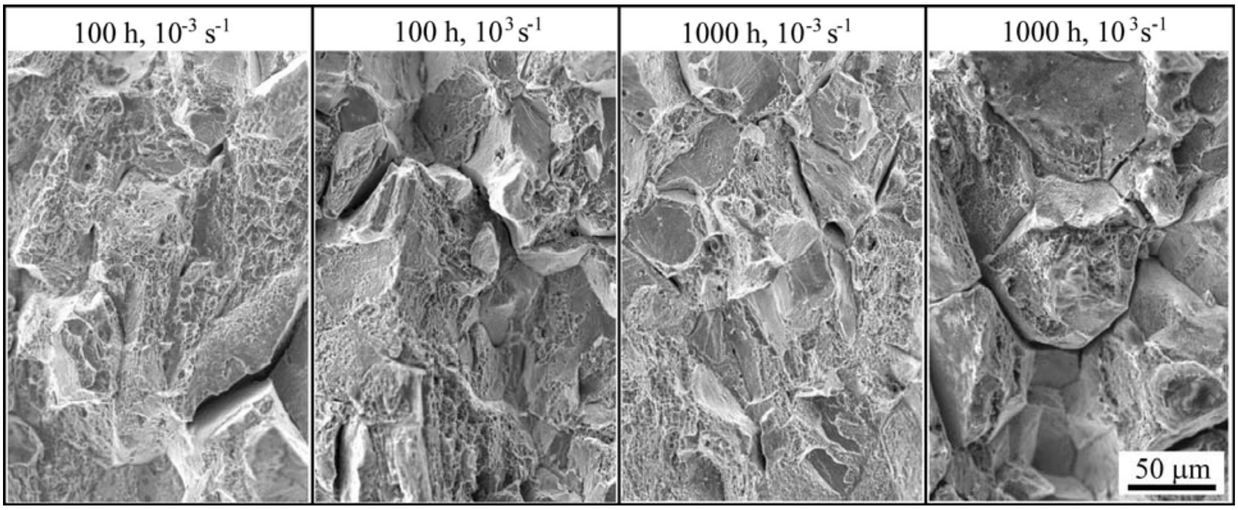

Figure 2. Tensile fracture morphologies in the alloy aged for different time at various strain rates

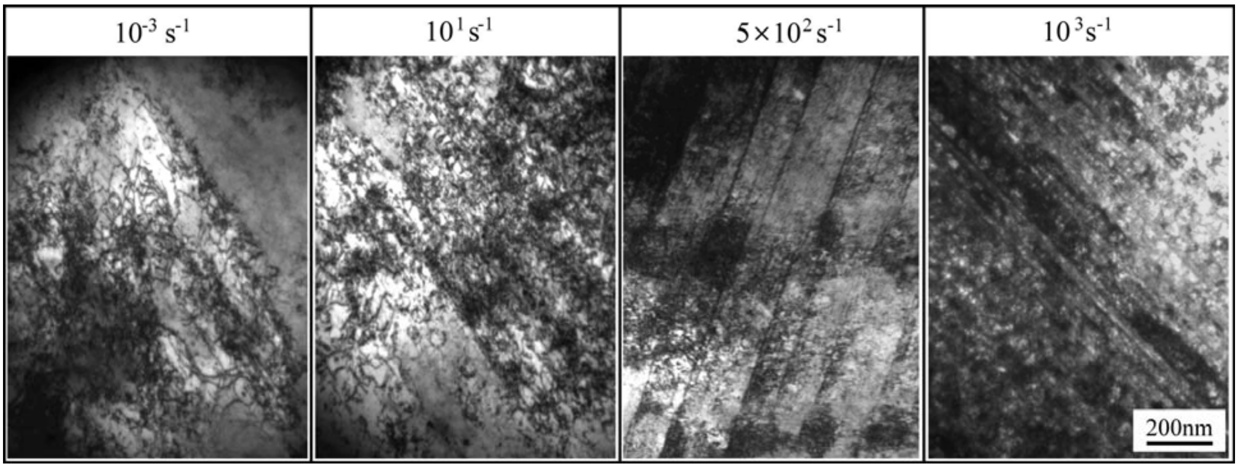

Figure 3. Dislocation configurations near fracture surface in the alloy aged for 200 h at various strain rates

3.4 Mechanism of strain rate effect on dynamic deformation behavior

The stress-strain curves of the alloy aged for 200 h with different strain rates are plotted in Figure 4. It indicates that there is no obvious change of the Young's modulus with the increase of the strain rate. Elastic limit and 0.2% offset yield strength of the alloy increase as the strain rate increase. From Figure 4, it is clear that the stress-strain curves in plastic deformation stage shows strong strain rate-dependence, which is consistent with the results shown in Figure 1. The strength of the alloy exhibits stronger strain rate sensitivity, when the strain rate is upto 10^{2} s^{-1}.

It is known that when the force component at a slip system reaches the critical value, the dislocation begins moving. In fact, the dislocation motion is the atom motion in lattice and thus the dislocation motion is time-dependent. As the applied stress increases, the dislocation motion speed increases rapidly. When the specimen undergoes a high loading rate, the acceleration which the dislocation motion needs will be also increased [11]. The dislocation will meet with obstacles continually when it begins moving and this resistance of dislocation motion presents the deformation resistance during plastic deformation from the macroscopic point of view [12]. It is clear that the higher the speed of movable dislocation become, the higher acceleration and resistance of dislocation motion will be.

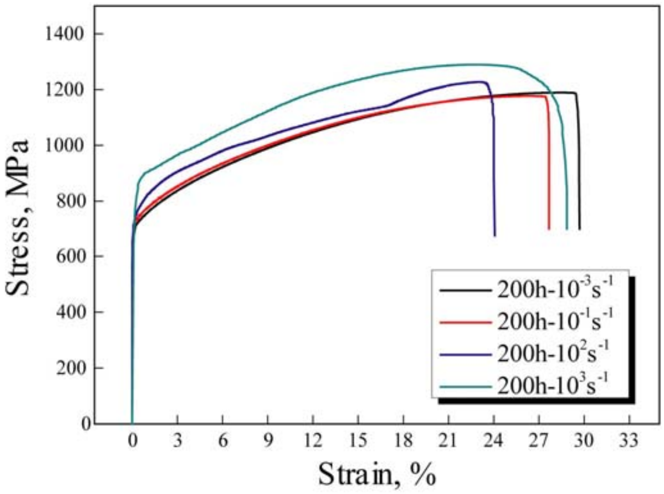

Figure 4. Stress-strain curves of the alloy aged for 200 h at various strain rates

Under the condition of static or quasi-static deformation, the speed of dislocation motion is higher than the deformation speed of materials by the low loading rate. Dislocations have relative enough time for acceleration. At the moment, the acceleration for dislocation moving is very lower, so the time-effect on deformation resistance is not obvious. Therefore, the increasing of yield strength is not high with the increasing of strain rate (lower than10^1 s^{-1}).

When the strain rate is higher than 10^1 s^{-1}, the acceleration of moving dislocation increases, meanwhile, the dislocation moving resistance increases. Consequently, the strength of the alloy increases significantly when the strain rate is higher than 10^2 s^{-1}. It has been found[13] that the dislocation motion is faster at the higher strain rate and the short-range factors inhibiting the dislocation motion such as the Peierls-Nabarro force, thermal vibration of the atoms and electron cloud resistance increases significantly. When the dislocation motion speed exceeds a certain value of about 10^1 $m{\cdot}s^{-1}$, the controlling mechanism of dislocation motion is changed from thermo-activation to short-range damping. And the dislocation motion resistance shows an obvious increase and thus the deformation resistance of the alloy rapidly increases. It indicates that the obvious increasing of the strength as the strain rate higher than 10^2 s^{-1} is related to such factor.

The compatible plastic deformation mechanism of dislocation pile-ups release and crystal rotating exhibits an obvious time-dependence in the alloy when tensile deformation under dynamic loadings [13-15]. And the plastic deformation coordinates by means of activation of dislocation slip systems, as shown in Figure 3. Dislocations are subjected to very high shear stress in a very short time and the shear stress reaches or exceeds the critical resolve shear stress (CRSS) of the dislocation slip systems when the dislocations are not yet ready to move at conventional dislocation slip systems. As a result, the ductility of the alloy shows a marked increase at the same strain rates range as that of the increasing strength.

On the other hard, a large amount of deformation twins have been found near the fracture surface in the alloy, as shown in Figure 5. And the number of deformation twins increases with the increasing of strain rate. Also some dislocation pile-ups around the stacking faults in the crystal can be observed under dynamic loading which is due to the stress concentration. When the dislocation motion is easy, the stress concentration is small. On the contrary, the stress concentration becomes high. It is too late for the dislocations at the dislocation pile-up to move in the alloy during tensile deformation at high strain rate, and thus the stress around the stacking fault increases, which will promote the occurrence of twinning deformation. The existence of a large number of deformation twins in the alloy during tensile deformation at high strain rate makes obvious contribution to increasing of the plastic deformation ability.

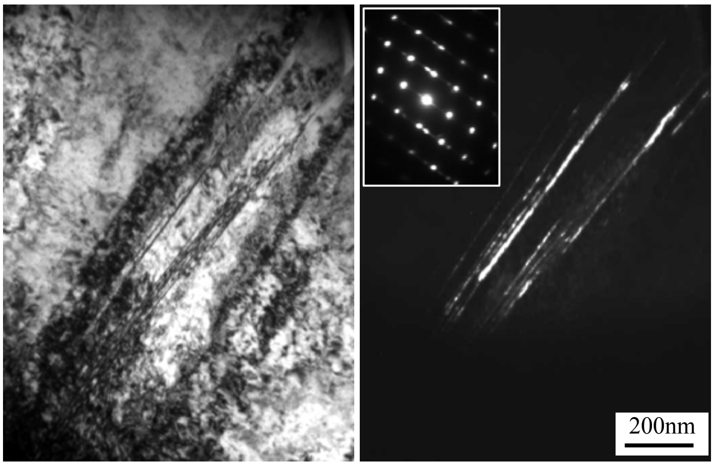

Figure 5. Deformation twins near the fracture surface in the alloy aged for 500 h at strain rate of 5×10^2 s^{-1}

At the same time, the thermal-softening effect often occur caused by heat generation during plastic deformation at higher strain rate [16, 17], which the dislocation moving resistance can be reduced, it also contributes to the increasing of the ductility of the alloy.

4. Conclusions

(1) The yield strength of the alloy exhibits a slight increase when strain rate is lower than 10^1 s^{-1}, while obvious increase when the strain rate is higher than 10^2 s^{-1}.
(2) The fracture elongation of the alloy shows obvious decrease when the strain rate is lower than 10^2 s^{-1}, whereas it shows a rapid increasing when the strain rate is higher than 10^2 s^{-1}.
(3) The deformation resistance of the alloy increases with the increasing of strain rate during deformation at high strain rate due to the increasing of short-range resistance caused by acceleration of dislocation motion. When the strain rate is higher than 10^2 s^{-1}, the significant increasing of the moving dislocation number is the main reason for the increasing of plastic deformation ability. In addition, the twinning deformations as well as thermal-softening caused by the temperature rising at high strain will contribute to the ductility of the alloy too.

Acknowledgements

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References

[1] S. L. Soo, R. Hood, D. K. Aspinwall, W. E. Voice, C. Sage, Machinability and surface integrity of RR1000 nickel based superalloy. CIRP Ann-Manuf Techn, 60(2011) 89-92.
[2] N. Fang , Q. Wu, A comparative study of the cutting forces in high speed machining of Ti-6Al-4V and Inconel 718 with a round cutting edge tool. J Mater Process Tech, 209(2009) 4385-4389.
[3] R. Sharghi-Moshtagh, S. Asgari, The effect of thermal exposure on the γ′ characteristics in a Ni-base superalloy. J Mater Process Tech, 147(2004) 343-350.

[4] W. S. Lee, C. F. Lin, Plastic deformation and fracture behaviour of Ti-6Al-4V alloy loaded with high strain rate under various temperatures. Mater Sci Eng, A241(1998) 48-59.
[5] X. C. Wei, R. Y. Fu, L. Li, Tensile deformation behavior of cold-rolled TRIP-aided steels over large range of strain rates. Mater Sci Eng, A465(2007) 260-268.
[6] S. Oliver, T. B. Jones, G. Fourlaris, Microstructure and dynamic material performance of high strength and ultra high strength strip steels. Mater Char, 58(2007) 390-396.
[7] R. Smerd, S. Winkler, C. Salisbury, M. Worswick, D. Lloyd, M. Finn, High strain rate tensile testing of automotive aluminum alloy sheet. Int. J. Impact Eng, 32(2005) 541-552.
[8] K. Ishikawa, H. Watanabe, T. Mukai, High strain rate deformation behavior of an AZ91 magnesium alloy at elevated temperatures. Mater Lett, 59(2005) 1511-1515.
[9] A. G. Odeshi, S. Al-ameeri, M. N. Bassim, Effect of high strain rate on plastic deformation of a low alloy steel subjected to ballistic impact. J Mater Process Tech, 162-163(2005) 385-391.
[10] X. Gong, J. L. Fan, B. Y. Huang, J. M. Tian, Microstructure characteristics and a deformation mechanism of fine-grained tungsten heavy alloy under high strain rate compression. Mater Sci Eng, A527(2010) 7565-7570.
[11] M. A. Meyers, Dynamic Behavior of Materials, in: National Defense Industry Press, Beijing, 2006, pp. 225-254.
[12] K. Rajeev, N. N. Sia, Comparison between high and low Strain-Rate deformation of tantalum. Metall Mater Trans, 31A(2000) 815-823.
[13] Y. Liu, L. Wang, S. S. He, F. Feng, X. D. Lu, B. J. Zhang, Effect of long-term aging on dynamic tensile deformation behavior of GH4169 alloy. Acta Metall Sin, 48(2012) 49-55.
[14] J. T. Liu, Z. G. Wang, J. K. Shang, Deformation behaviors of [110] and [112] oriented β-Sn single crystal. Acta Metall Sin, 44(2008) 1409-1414.
[15] Z. L. Liu, X. C. You, Z. Zhuang, A mesoscale investigation of strain rate effect on dynamic deformation of single-crystal copper. Int J Solids Struct, 45(2008) 3674-3687.
[16] K. Rajeev, N. N. Sia, Determination of temperature rise during high strain rate deformation. Mech Mater, 27(1998) 1-12.
[17] A. Rusinek, J. R. Klepaczko, Experiments on heat generated during plastic deformation and stored energy for TRIP steels. Mater Des, 30(2009) 35-48.