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Origin of Serration during Deformation at High Temperature in Alloy 600

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1. Introduction

It was recently reported that an ordering reaction occurs in Alloy 600 [1, 2] and a PWSCC mechanism based on an ordering reaction has been proposed [3]. However, there has been little investigation on the effects of ordering reaction on the mechanical behavior.

Alloy 600 shows a plateau of the ultimate tensile strength (UTS) and serration in the 150 ~ 500 °C region; a rapid drop of UTS and a minimum of elongation and reduction of area at around 600°C. The occurrence of serration is thought to be due to the interaction between an interstitial atom and mobile dislocation, namely, dynamic strain aging (DSA). However, it seems that the interaction between an interstitial atom and a dislocation in a wide temperature range is not feasible. The DSA occurs only if both the diffusion rate and glide of the dislocation is similar because the diffusion rate of an interstitial atom increases with temperature exponentially.

There is no proper explanation for this phenomenon at present. Thus, high temperature mechanical tests were carried out up to 745℃, and the results are interpreted and the reason why the plateau of UTS appears in Alloy 600 is discussed by the effect of ordering reaction.

2. Experimental

A round type tensile specimen with a thread in the grip region was machined using an Alloy 600 rod with 10 mm diameter. The chemical composition is shown in Table 1. Tensile tests were carried out at RT to 745℃ using an MTS model 810 tester. The strain rate varied from 10^{-2}/s to $3.3x10^{-5}$/s. The total elongation and reduction of area are calculated by a change in the gauge length and diameter after testing.

The deformed regions of the tensile specimens at various temperatures have been examined by a micro Vickers hardness tester, transmission electron microscope (TEM), and differential scanning calorimeter (DSC), and through neutron diffraction. The lattice contraction during tensile tests was calculated using the center gravity of the diffraction peaks.

3. Results

The microstructure of solution annealed Alloy 600 and aged Alloy 600 is shown in Fig. 1. Twinning appeared in the aged specimen at 475℃ for 10,000 hours, but not in the solution annealed specimen. This means that there is internal variation during annealing at 475℃.

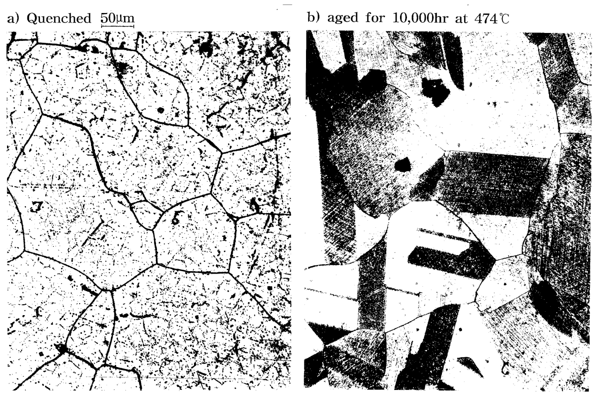

Fig. 1. Optical micrographs of Alloy 600, a) solution annealed (SA) and b) aged at 475℃ for 10,000 hours.

The results of the yield, tensile, elongation, and reduction of area with a strain rate of 10^{-4}/s are compared with the trend of specific heat in Fig. 2. The trend of specific heat shows a transition of ordering to disordering between 520 and 580℃. The yield strength decreases with temperature monotonically. However, the UTS decreases with temperature below 200 ℃, and maintains a similar value between 200 and 500 ℃, and decreases rapidly above 500 ℃. The trend of UTS is very similar to uniform elongation. An elongation minimum appeared at around 600 ℃. The plateau of UTS appears in the ordering temperature region and the elongation minimum appears in the disordering region. It is possible to understand that an ordering reaction has a significant potential to the mechanical behavior of Alloy 600.

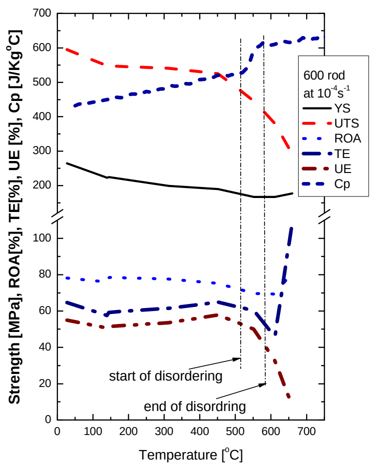

Fig. 2. Comparison of mechanical properties with specific heat variation.

Fig. 3 shows the results of DSC in the 40% deformed region of the tensile specimen. The tensile deformed specimen at RT and 145 ℃ shows a relatively large exothermic reaction. However, that at 313 ℃ shows a smaller reaction and that above 452 ℃ shows no exothermic reaction. This means that an ordering reaction occurs simultaneously during tensile deformation.

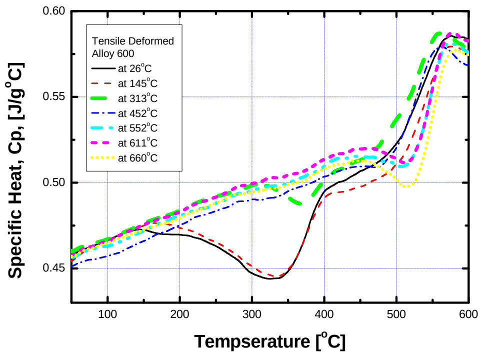

Fig. 3. The trend of specific heat with tensile testing temperature.

The fact that ordering reaction in Alloy 600 causes exothermic reaction is explained in detail in Ref. [1-4]. The exothermic reaction is due to increase in number of favorable atomic bond. This process is a ordering reaction. Thus, it is possible to understand that the ordering reaction during tensile deformation causes a plateau of UTS in this temperature region.

Fig. 4 shows the Vickers hardness measured in the 40% strained region with the tensile temperature. The maximum hardness appears at around 450 ℃. This is a surprising result because deformation at a high temperature causes hardening and annealing effects simultaneously and thus show a slightly lower hardness. This result means that there is a certain strengthening effect in this temperature region. This effect comes from the ordering reaction.

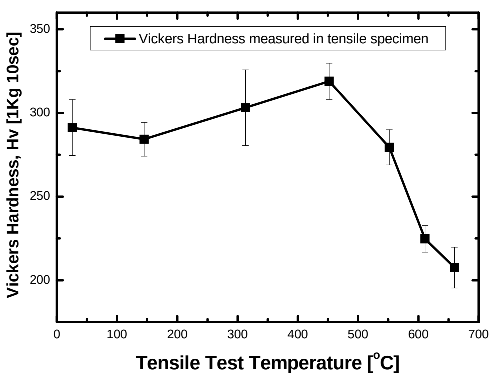

Fig. 4. Vickers hardness with tensile temperature in a 40% strained region.

Fig. 5 shows the lattice contraction behavior of a tensile specimen with temperature. The lattice contraction appears between 160 and 600°C. This means that the ordering reaction is enhanced by deformation in this temperature region. The strain rate may affect the ordering temperature. Fig. 2 comes from the specimen deformed at $2x10^{-4}$/s, whereas Fig. 5 is at $2x10^{-3}$/s. This is why the results have a slight difference in temperature scale. It is expected that the temperature region may be shifted to a higher temperature if the strain rate becomes faster.

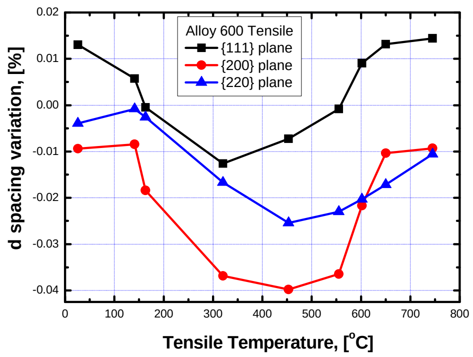

Fig. 5. The lattice contraction measured by neutron diffraction using tensile specimen tested at $2x10^{-3}$/s.

4. Conclusions

The occurrence of the plateau of UTS and serration during the tensile tests is due to an ordering reaction in Alloy 600. The ordering reaction provides an extra strengthening effect at high temperature, which is effective until a disordering reaction occurs. The lattice contraction during the tensile tests is due to strain induced ordering. The high temperature mechanical behavior can be explained by the ordering reaction and its effects.

Acknowledgements

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REFERENCES

[1] S. Kim, I. L. Kuk, and J. S. Kim, Materials Science and Engineering **A279**, 142, 2000.

[2]. S. Kim, J. Kim, and H. Kim, Journal of Korean Metal and Materials, **44**, 473, 2006.

[3] S. S. Kim, J. S. Kim, S. S. Hwang, and H. P. Kim, 'Proceedings of Korean Nuclear Society 2008 Fall Meeting', p. 237.

[4] S. S. Kim, D. W. Kim, and Y. S. Kim, Journal of Korean Metal and Materials, **50,** 703(2012).