DE GRUYTER DOI 10.1515/htmp-2013-0065 — High Temp. Mater. Proc. 2014; 33(5): 453–461

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Effect of Reheat Treatment on Microstructural Refurbishment and Hardness of the As-cast Inconel 738

Abstract: This work investigates the effect of rejuvenation heat treatment conditions for refurbishment of the long-term serviced gas turbine blades, which were made of as-cast nickel base superalloy grade, Inconel 738. The reheat treatment conditions consist of solutionizing treatments at temperatures of 1,438, 1,458 and 1,478 K for 14.4 ks and aging treatments at temperatures of 1,133, 1,148 and 1,163 K for 43.2, 86.4, 129.6 and 172.8 ks. The results show that increase in aging times results in continuous increase of size and area fraction of gamma prime (γ') particles. The higher solutionizing temperature leads to the lower area fraction and smaller size of gamma prime particles. Regarding the microstructure characteristics, the most proper reheat treatment condition should be solutionizing at temperature of 1,438 K for 14.4 ks and aging at temperature of 1,133 K for 172.8 ks, which provides the highest area fraction of gamma prime particles in proper size.

Keywords: reheat treatment, microstructure, hardness, refurbishment, Inconel 738

PACS® (2010). 81.05.Bx, 81.40.Cd

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1 Introduction

In the present time, many power plants in Thailand use stationary or land-based gas turbine engines to generate electricity for domestic consumption. After service for some decades, these land-based gas turbine engines need maintenance. Especially, the replacement and/or refurbishment of hot components are very necessary. The highest material cost in these engines is the cost of turbine blade components, which are made of expensive nickel based superalloys in various grades. In general, turbine blades are in service at elevated temperatures for long term under very high loads. This condition could induce microstructural degradation of turbine blade, resulting in lower mechanical properties and service life time. Because mechanical properties of turbine blade are strongly related to the microstructures, many previous research works [1–20] have been carried out to investigate the relationship between microstructure and mechanical properties. The microstructural degradation mainly involves coarsening or rafting of γ' precipitated particles, resulting in lower volume or area fraction of γ' particle as well as lower effect of strengthening mechanism for the material.

In order to restore the proper microstructural characteristics and mechanical properties, refurbishment reheat treatment is vitally needed for reducing material cost in further service. Generally, reheat treatment for as-cast nickel-based superalloy consists of two major heat treatment steps, which are solution treatment in order to dissolve all coarse γ' particles into the gamma matrix and aging treatment to reprecipitate the dense and uniform γ' particles with proper size.

There are many research works [10–11, 13–25] investigating the effect of reheat treatment conditions on the obtained microstructure in cast nickel-based superalloys of various grades, including works [1, 21–32] on Inconel 738. The previous studies [1] indicated that the proper reheat treatment procedure should include solutionizing Inconel 738 in the temperature range of 1,398–1,478 K for 7.2–21.6 ks followed by a rapid gas quench (25 K to 55 K/min. to below 923 K), then aging at 1,118 K for 86.4 ks followed by a rapid gas quench to room temperature. Some research works [1, 22–24] have reported that the lower solutionizing temperature in the range of 1,398–1,418 K, which are the standard solutionizing temperature for Inconel 738 [33, 34], could not dissolve the coarse γ' particles completely, resulting in γ'-bimodal microstructure. Therefore, the alloys need to be solutionized at higher temperatures than

Table 1: Chemical composition in weight% of the as-cast Inconel 738

Ni	Cr	Co	Ti	Al	W	Mo	Ta	Nb	C	Fe	B	Zr
Bal.	15.84	8.5	3.47	3.46	2.48	1.88	1.69	0.92	0.11	0.07	0.12	0.04

the standard reheat treatment temperature of 1,398–1,418 K. The higher solutionizing temperature provides higher solubility of coarse γ' in the gamma matrix, resulting in dissolving the coarse γ' particles completely into the gamma matrix during solutionizing. Then, the microstructure after long-term service could be fully restored after aging. However, the applied higher solutionizing temperature conditions provide lower area fraction of γ' phase, comparing with the standard reheat treatment condition [28, 31, 32].

This research work has an aim to enhance microstructural characteristics by applying higher solutionizing and aging temperatures as well as longer aging duration for refurbishment of Inconel 738.

Table 2: Reheat treatment conditions

*Solutionizing temperature (K)/14.4 ks	*Aging temperature (K)	Aging time (ks)
1,438	1,133	43.2, 86.4, 129.6, 172.8
1,438	1,148	43.2, 86.4, 129.6, 172.8
1,438	1,163	43.2, 86.4, 129.6, 172.8
1,458	1,133	43.2, 86.4, 129.6, 172.8
1,458	1,148	43.2, 86.4, 129.6, 172.8
1,458	1,163	43.2, 86.4, 129.6, 172.8
1,478	1,133	43.2, 86.4, 129.6, 172.8
1,478	1,148	43.2, 86.4, 129.6, 172.8
1,478	1,163	43.2, 86.4, 129.6, 172.8

* Air cooling after both solutionizing and aging

2 Materials and experimental procedure

The material under investigation is the as-received cast nickel-based superalloy turbine blade, grade Inconel 738, after long-term service at elevated temperatures from Electricity Generating Authority of Thailand (EGAT). The composition of the as-received cast nickel-based superalloy, Inconel 738 is shown in Table 1.

For the studied specimens, approximately 1-cm^2 rectangular plates were cut from the most severe degradation zone of turbine blades. The solutionizing and aging treatments of specimens were carried out in a vacuum furnace. After both solutionizing and aging, the specimens were cooled in air. The experimental reheat treatment conditions are shown in Table 2. Microstructures of reheat treated specimens were observed from the cross-section surface to compare with those of parallel grinded and polished surface of turbine blades. All samples were polished using standard metallographic techniques and subsequently etched in Marble etchant, which has chemical composition of 10-g $CuSO_4$, 50-ml HCl, and 50-ml H_2O. The microstructures of heat treatment samples were studied by scanning electron microscope with secondary electron mode. The area fraction of γ' particles and average areas per γ' particle or average size were determined by using image analyzer. Vicker microhardness (HV) of all samples was measured by using 500-g load.

3 Results and discussion

3.1 As-received microstructure after long-term service

Figure 1a) shows the microstructure of as-cast nickel-based superalloy, Inconel 738, turbine blade after long-term service. It is observed that the original uniform size distribution of γ' particles had been changed during long-term service. The present structure shows both small and big sizes of γ' in matrix, which indicates bimodal γ' precipitation. This could indicate that there was coarsening mechanism of γ' particles to reduce internal energy during long-term service at elevated temperatures. The coarse γ' particles have diameter up to 1 µm, approximately, and the very fine γ' particles have average diameter of about 0.125 µm. These microstructural characteristics theoretically provide the lower creep strength due to the effects of large γ' particle size and lower volume fraction of fine γ' particles in general cases [1, 33–34].

3.2 Microstructures after solutionizing treatments

Figures 1b)–1d) show microstructures of the as-received turbine blades after solution treatment at temperatures of 1,438, 1,458 and 1,478 K for 14.4 ks, respectively. From these

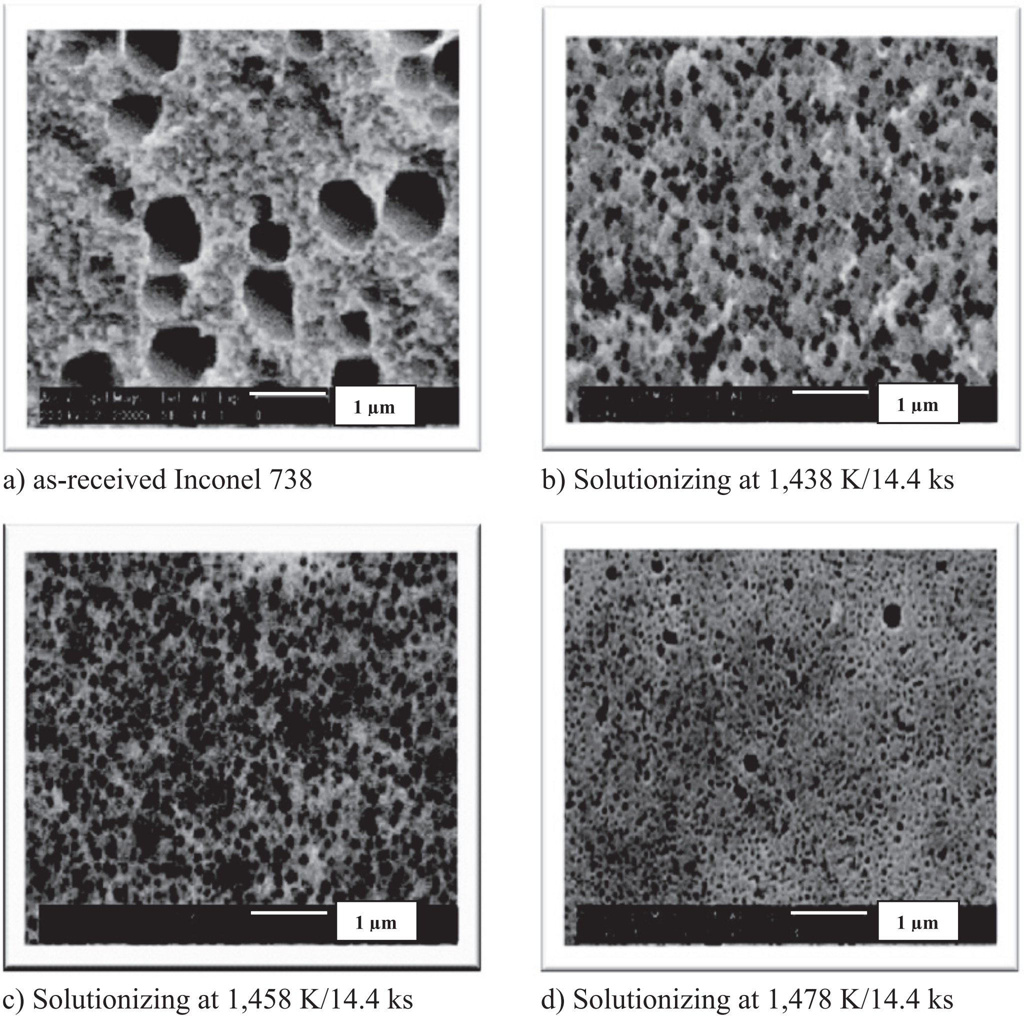


Fig. 1: Microstructures of Inconel 738 from various conditions observed by SEM.

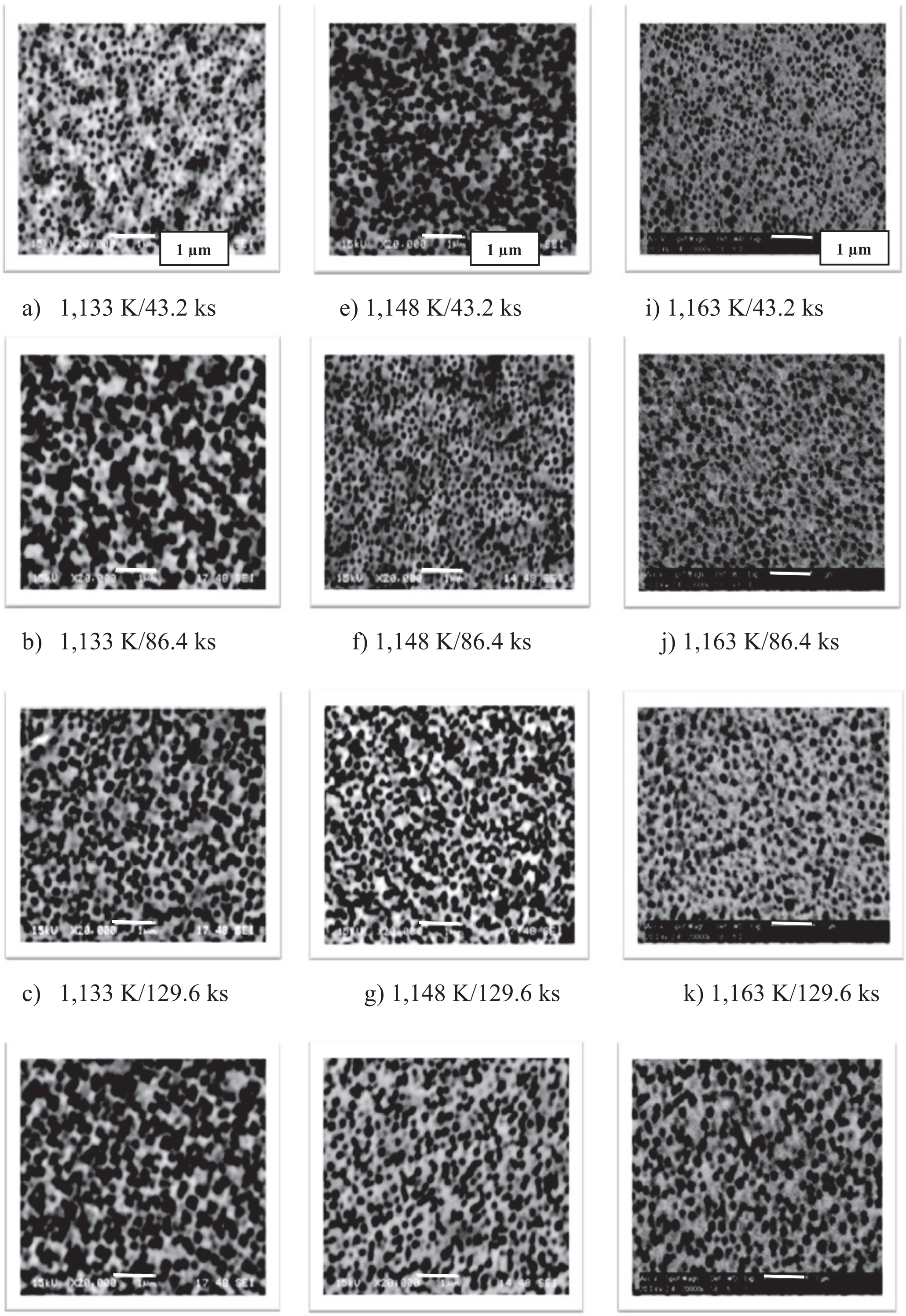
Figures, it is found that the higher solutionizing treatment temperature provided the higher dissolution of coarse γ' particles into the gamma matrix. All solutionizing treatment temperatures could dissolve homogeneously almost coarse γ' particles into the matrix and leave the uniform fine to very fine γ' particles in the matrix depending on solutionizing temperature. It should be noted that the higher solutionizing temperature also results in the more different reprecititation of very fine γ' particles during air cooling. The higher solutionizing temperature provides the shorter cooling duration to room temperature, resulting in the finer γ' particles. This could happen because of less diffusion time for γ' precipitation.

3.3 Microstructures after solutionizing and reheat treatments

Figures 2, 3 and 4 show the microstructures after the experimented solutionizing and reheat treatments. For easy understandable discussions, the summaries of average size and area fraction of γ' particles according to all experiments are shown in Figures 5 and 6, respectively.

Figures 2a)–2l) show microstructures after various reheat treatments with solutionizing treatment at temperature of 1,438 K for 14.4 ks and aging treatment at temperatures of 1,133, 1,148 and 1,163 K for 43.2, 86.4, 129.6 and 172.8 ks. From Figures 2a)–2l), it can be observed that average size and area fraction of γ' particles increase with longer aging duration, see Figures 5 and 6. A longer aging duration results in higher precipitation and growth of γ' particles for all aging temperatures. In these cases, the different aging temperatures impose minor impact on the area fraction and average particle size, see Figures 5 and 6.

Figures 3a)–3l) show reheat treated microstructures with solutionizing temperature of 1,458 K for 14.4 ks with aging temperatures of 1,133, 1,148 and 1,162 K for 43.2, 86.4, 129.6 and 172.8 ks, respectively. From these Figures, it is found that the area fraction of γ' particles after all aging



a) 1,133 K/43.2 ks e) 1,148 K/43.2 ks i) 1,163 K/43.2 ks

b) 1,133 K/86.4 ks f) 1,148 K/86.4 ks j) 1,163 K/86.4 ks

c) 1,133 K/129.6 ks g) 1,148 K/129.6 ks k) 1,163 K/129.6 ks

d) 1,133 K/172.8 ks h) 1,148 K/172.8 ks l) 1,163 K/172.8 ks

Fig. 2: Microstructures of specimens after solutionizing temperature of 1,438 K/14.4 ks and various aging conditions

temperatures increase with aging time, see Figure 5. Furthermore, the average sizes of γ' particles in each aging temperature are nearly the same but increase with aging time, as shown in Figure 6. This observed result is similar to the case of solutionizing temperature of 1,438 K for 14.4 ks.

In case of the solutionizing temperature of 1,478 K for 14.4 ks, the received reheat treated microstructures after

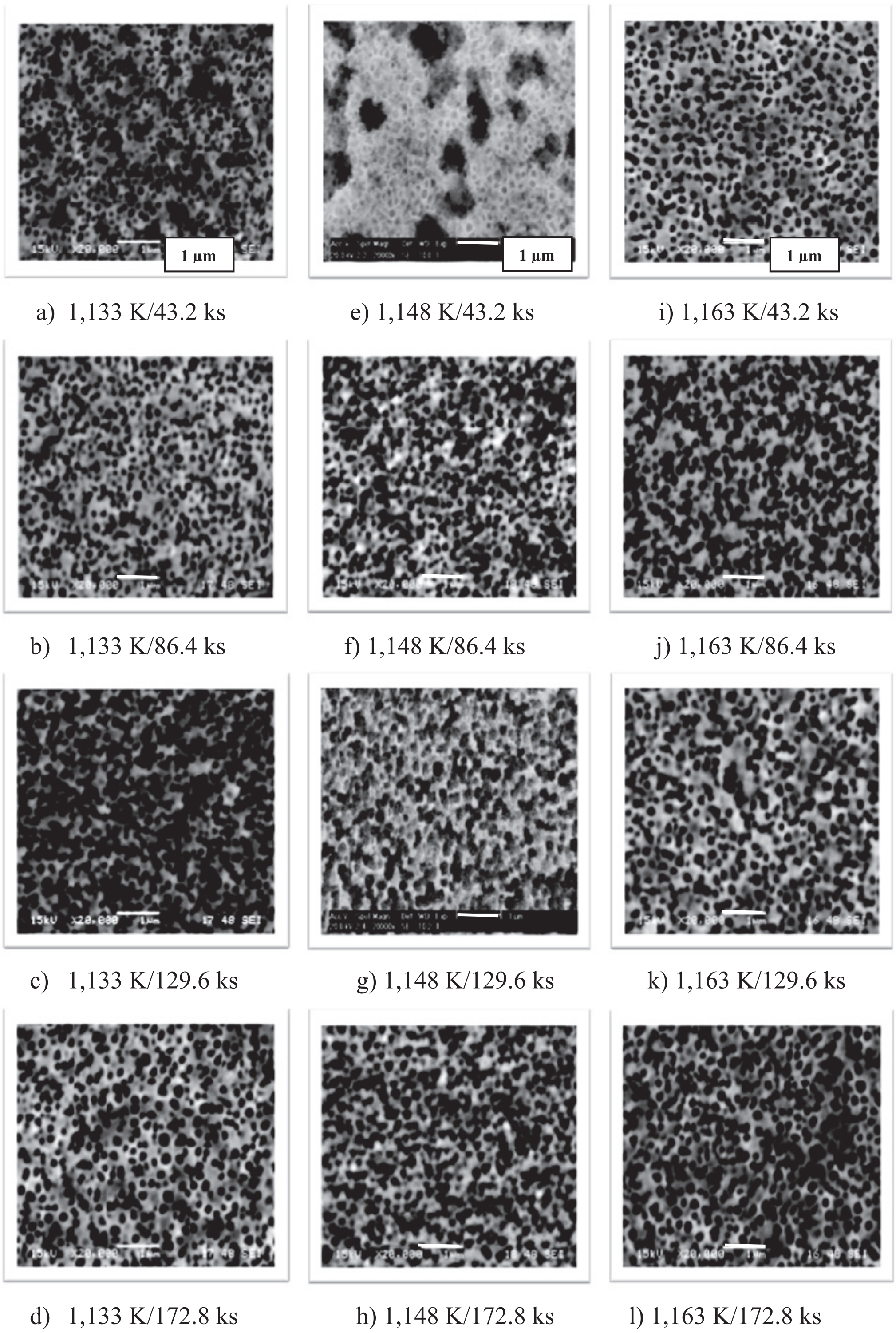


Fig. 3: Microstructures of specimens with solutionizing temperature of 1,458 K/14.4 ks and various aging conditions

different aging temperatures are illustrated in Figures 4a)–4l). The area fraction and average sizes of γ' particles also increase with aging time as shown in Figures 5 and 6. The different aging temperatures did not provide any significant different effect on area fraction and average sizes of γ' particles in this case.

From Figures 2–6, it can be summarized that the solutionizing temperature of 1,438 K for 14.4 ks should provide

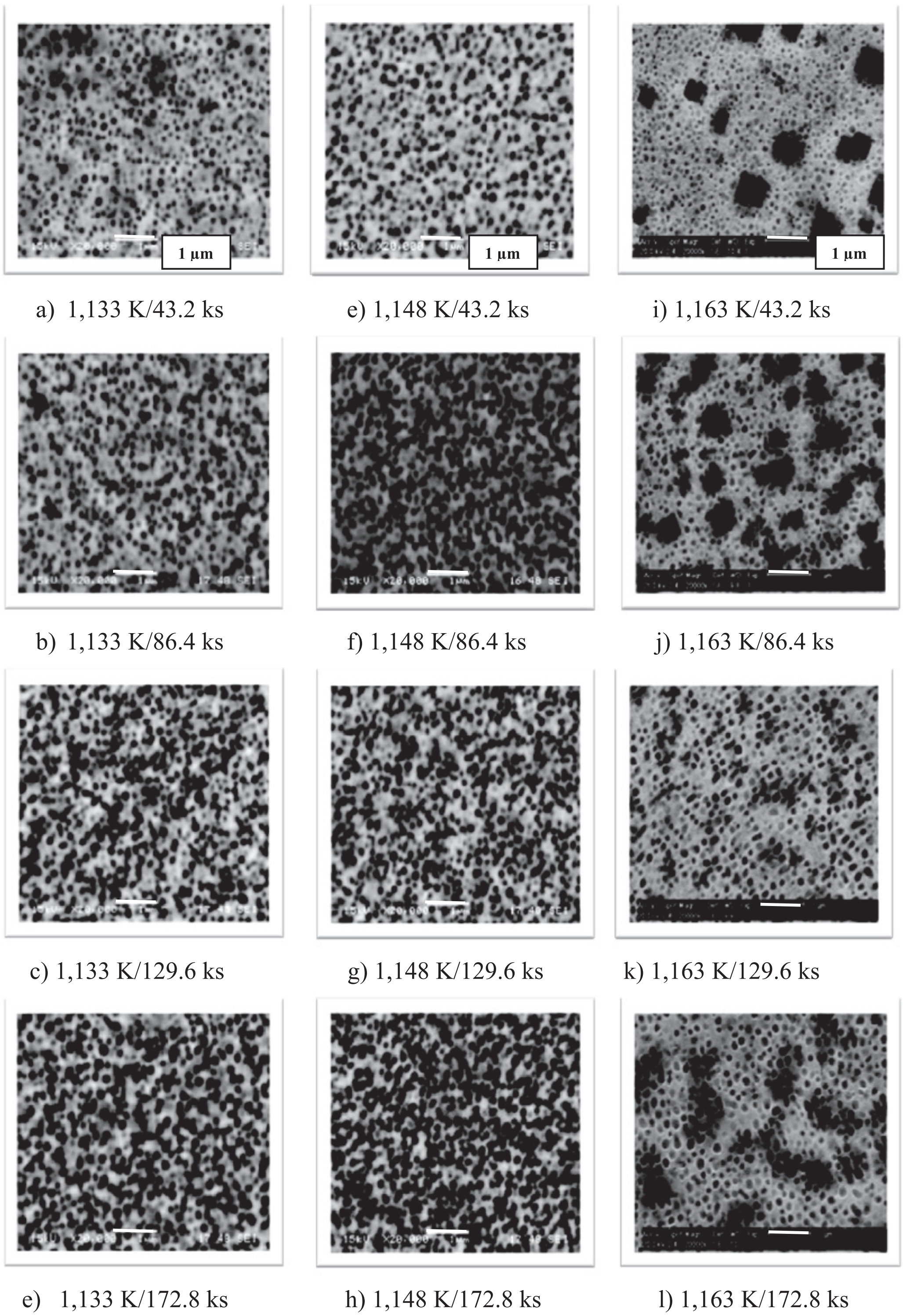


Fig. 4: Microstructures of specimens with solutionizing temperature of 1,478 K/14.4 ks and various aging conditions

the most proper microstructural characteristics with both maximum average size and area fraction of γ' particles. This may be because the higher solutionizing temperatures of 1,458 and 1,478 K allow element atoms, which formed γ' particles, to diffuse from grain interior to grain boundary in longer distance, resulting in lower amount of those atoms inside the grain available to form γ' particles during aging. It is well known that the $M_{23}C_6$ and MC carbide particles are possibly present at the grain boundary of superalloy [33, 34]. These M elements could be Cr,

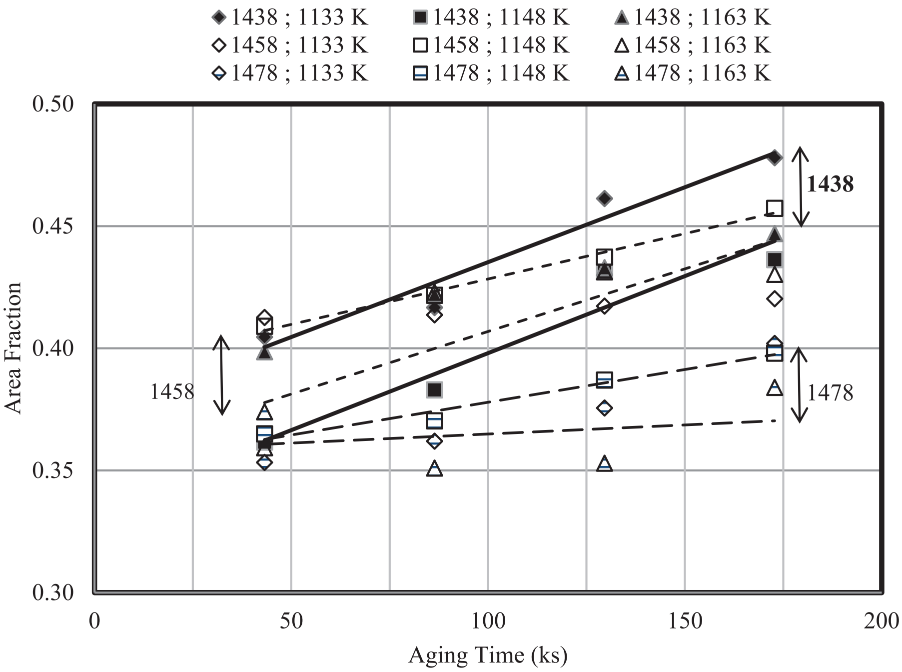


Fig. 5: Area fraction of γ′ particles at various aging times of each aging temperature after solutionizing temperatures of 1,438, 1,458 and 1,478 K for 14.4 ks

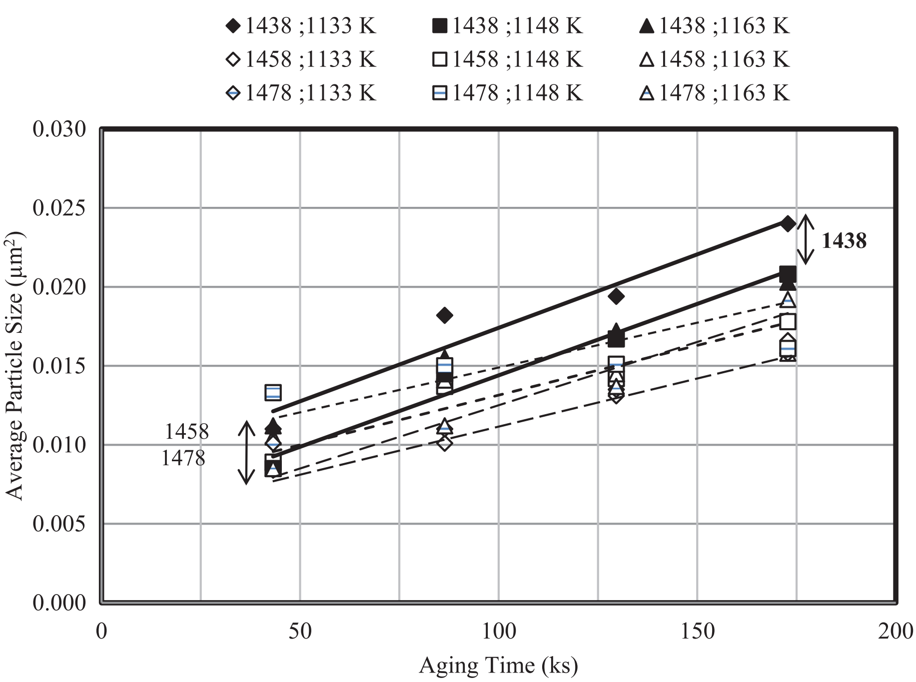


Fig. 6: Average particle size of γ′ particles at various aging times of each aging temperature after solutionizing temperatures of 1,438, 1,458 and 1,478 K for 14.4 ks

Ti, Ta, Nb. Ni, Al, Ti, Ta and Nb are the γ'-particle forming elements. The $M_{23}C_6$ can be decomposed at the higher solutionizing temperature resulting in the free carbon which has the high affinity with Ti, Ta and Nb to from MC carbide. Therefore, the diffusion of element atoms forming γ' particles from grain interior to grain boundary is possible. Considering the effect of aging temperatures after solutionizing at temperature of 1,438 K for 14.4 ks, it seems that the aging temperature of 1,133 K for 129.6 ks is the most proper aging temperature among these cases, because of the highest volume fraction and average size of γ' particles for all aging times, see Figures 5 and 6.

3.4 Hardness test

The hardness test results after all experiments are shown in Figure 7. It seems to be difficult to differentiate the effect of solutionizing and reheat treatments on the hardness. However, it can be observed that solutionizing at temperature of 1,438 K for all aging temperatures and times provides the lowest hardness. By aging at temperature of 1,163 K for all times and all solutionizing treatments, it provides lower hardness than aging at temperatures of 1,133 and 1,148 K. From Figure 7, the hardness values of approximately 460–500 HV are obtained when solutionizing at temperatures of 1,458 and 1,488 K for 14.4 ks and aging at temperatures of 1,133 and 1,148 K. Regarding these high hardness values from this experiment, the proper reheat treatment conditions are different from those regarding the microstructure characteristics. However, hardness should not be used as the sole criteria for selection. From the application viewpoint, further investigation of creep resistance is of great significance. For microstructural refurbishment of the used superalloys, the microstructure characteristics should be first considered to select the most proper reheat treatment condition [1, 33, 34].

4 Conclusions

From this experiment, the conclusions can be drawn as follows:

1. The higher solutionizing temperatures provides the precipitation of finer γ' particles and lower areas fraction of γ' particles.
2. Increase in aging duration results in more γ' phase precipitation with higher area fraction and average areas per particle (size) of γ' particles.
3. The most proper aging temperature for all solutionizing temperatures is 1,133 K, which provides the maximum area fraction and average size of γ' particle.
4. The most proper reheat treatment condition to provide the most suitable microstructural characteristics is solutionizing at temperatures of 1,438 K for 14.4 ks and aging at temperature of 1,133 K for 129.6 ks.
5. From the hardness, the proper reheat treatment conditions to provide the hardness values higher than 450 HV are solutionizing at temperatures of 1,458, 1,478 K for 14.4 ks and aging at temperatures of 1,133 and 1,148 K.

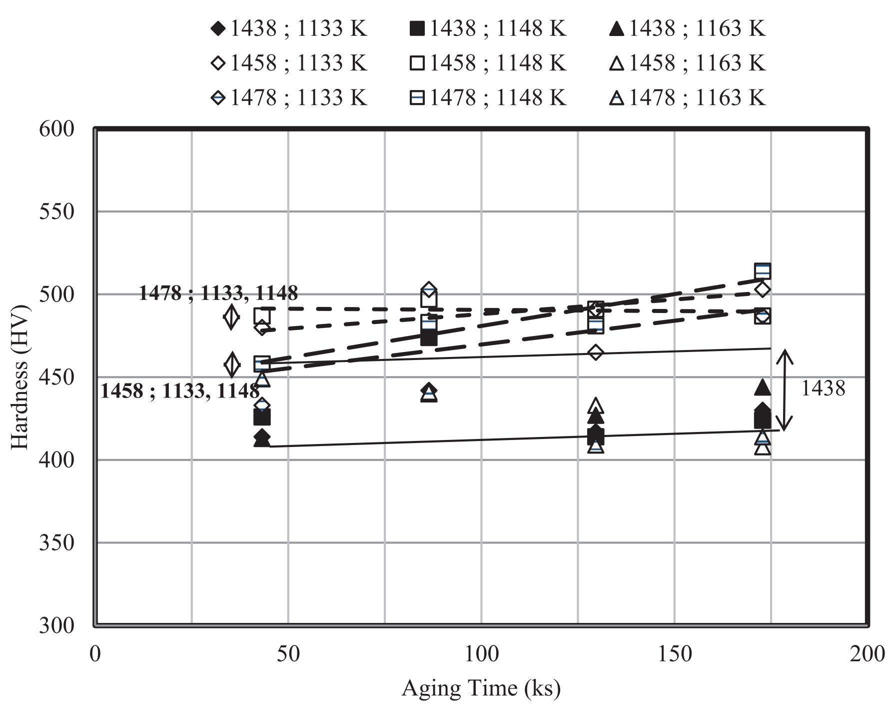


Fig. 7: Average hardness at various aging times of each aging temperature after solutionizing temperatures of 1,438, 1,458 and 1,478 K for 14.4 ks

Acknowledgments: The present research work was financially granted by "Integrated Innovation Academic Center: IIAC Chulalongkorn University Centenary Academic Development Project. This work was also partially supported by the Higher Education Research Promotion and National Research University Project of Thailand, Office of the Higher Education Commission (Project Code: AM1010A).

Received: July 11, 2013. Accepted: November 27, 2013.

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