Relative Influence of Different Factors on Young's Modulus in Nickel and Zirconium base Alloy Systems upon Precipitation of Intermetallics

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Abstract. The influence of precipitation of intermetallics on changes in Young's modulus of nickel and zirconium base alloys has been discussed in this paper. This study indicates that the change in the modulus due to thermal ageing in these alloys is essentially governed by the change in the modulus of the matrix due to removal of precipitation forming elements.

1.0 Introduction

Mechanical properties in various precipitation hardening alloys, such as aluminum base, nickel base and iron base (ferritic and maraging steels) alloys, are derived through controlled precipitation of different intermetallic phases. Ultrasonic measurements have been used for characterization of precipitation behaviour in these alloy systems [1-4]. In most of the alloy systems, ultrasonic velocity has been found to increase with the precipitation of various intermetallic phases, irrespective of the type of the precipitates. The increase in the ultrasonic velocity has been attributed essentially to increase in the Young's modulus of the alloy. In the presence of precipitates, the material can be considered as a composite of three components, i.e. matrix, matrix-precipitate interface and precipitate. Since, ultrasonic velocity depends on the Young's modulus and density of the material [5], it is dependent upon the Young's modulus and density of these three components [4]. The Young's modulus of a precipitated alloy is governed by the changes in the modulus of (1) matrix due to changed composition, (2) intermetallic precipitates and (3) precipitate-matrix interface. Even though several studies have been carried out to understand the influence of precipitation on the average elastic moduli as reflected in ultrasonic velocity, very few attempts have been made to probe into the individual influences of the abovementioned three components.

In the present study, ultrasonic velocity measurements have been carried out for studying the variations in Young's modulus of two nickel base superalloys (Inconel 625 and Nimonic PE 16) and one zirconium base alloy (Zircoloy-2) upon precipitation of different intermetallic phases. The study indicates that the change in the modulus due to precipitation of intermetallic phases in nickel and zirconium base alloys is essentially governed by the change in the modulus of the matrix due to removal of precipitation forming elements.

2.0 Experimental

Table I gives the chemical composition (wt%) of the two nickel base superalloys investigated in the present study. Various specimens of Inconel 625 were obtained from the service exposed (~873 K for ~60000 h) tube of 110 mm diameter and given suitable heat treatments to dissolve various types of precipitates preferentially and also to precipitate out the new phases. The specimens from service exposed material were heat treated at different temperatures (923 K, 1023 K and 1123 K) for durations upto 500 h and one of the specimens was solution annealed at 1323 K for 1 h in order to dissolve all the precipitates [3].

Nimonic PE 16 specimens were solution annealed at 1323 K for 1 h followed by thermal ageing at different temperatures in range of 873 K to 1073 K for durations up to 24 h [6].

Table I. Chemical composition (wt%) of nickel base superalloys Inconel 625 and Nimonic PE16

Alloy	Cr	Mo	Fe	Nb	C	Mn	Si	Al	Ti	Co	Ni
Inconel 625	21.7	8.8	3.9	3.9	.05	.14	.15	.17	.23	.08	Bal.
PE-16	16.5	3.3	33.8	--	.07	.4	.26	1.24	1.2	.27	Bal.

The chemical composition (wt %) of Zircoloy-2 used in this study is as follows: Sn-1.62, Fe-0.18, Cr-0.1, Ni-0.06 and Zr-balance. Several specimens of Zircaloy-2 were given a common β-quenching treatment at 1223 K for 2 h followed by water quenching. These specimens were then isochronally aged for 1 h in the temperature range of 473 to 973 K [7].

Ultrasonic longitudinal and shear wave velocities and density have been precisely measured in all these specimens. The details of the experimental setup for ultrasonic velocity and density measurements are reported elsewhere [3, 7]. Young's modulus for each specimen has been computed from the measured velocity and density values using the following equation:

$$E = \rho V_t^2 \frac{\left(3V_l^2 - 4V_t^2\right)}{\left(V_l^2 - V_t^2\right)} \qquad (1)$$

where ρ is the density, V_l is the longitudinal wave velocity and V_t is the transverse wave velocity.

3.0 Results and Discussion

Figure 1 shows the variations in Young's modulus with post service thermal ageing in Inconel 625. It can be seen very clearly from this figure that the Young's modulus of Inconel 625 is minimum (201 GPa) in the solution annealed condition and it increases with the precipitation of various intermetallic phases upon service exposure at elevated temperature (marked as SE) or thermal ageing. The increase in ultrasonic velocity upon service exposure is attributed to extensive precipitation of two different types of intermetallic precipitates, $Ni_2(Cr,Mo)$ and γ'' [$Ni_3(Nb,Al,Ti)$] [3]. The increase in the ultrasonic velocity upon post service heat treatment at 1123 K beyond 1 h is attributed to the precipitation of intermetallic phase δ [$Ni_3(Nb)$].

Figure 2 shows the variations in Young's modulus and hardness with volume fraction of γ' [$Ni_3(Al,Ti)$] phase precipitated in Nimonic PE 16 upon ageing at temperatures in the range of 873 K to 1073 K for durations up to 24 h. It can be seen from this figure that Young's modulus increases with the volume fraction of intermetallic phase γ'.

In both the nickel base superalloys, Young's modulus is found to increase with the precipitation of intermetallic phases, such as γ'', $Ni_2(Cr,Mo)$ and δ in Inconel 625 and γ' in Nimonic alloy PE 16. As discussed earlier, the Young's modulus of a precipitated alloy is governed by the changes in the modulus of (1) intermetallics precipitates (2) precipitate-matrix interface and (3) matrix with changed composition.

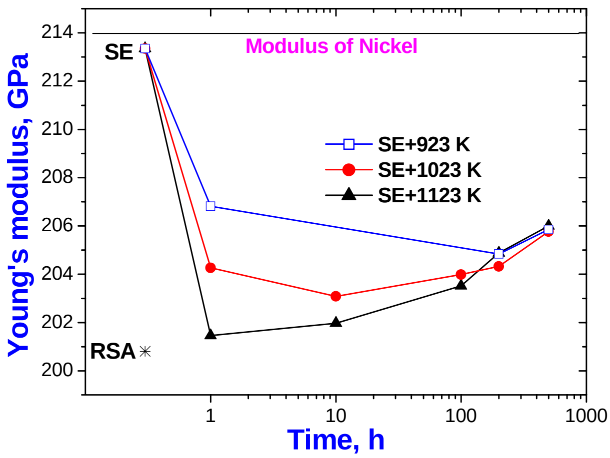

Fig. 1. Variation in Young's modulus with post service thermal ageing in Inconel 625 (SE-service exposure and RSA- re-solution annealed). Modulus of pure nickel is also shown for direct comparison.

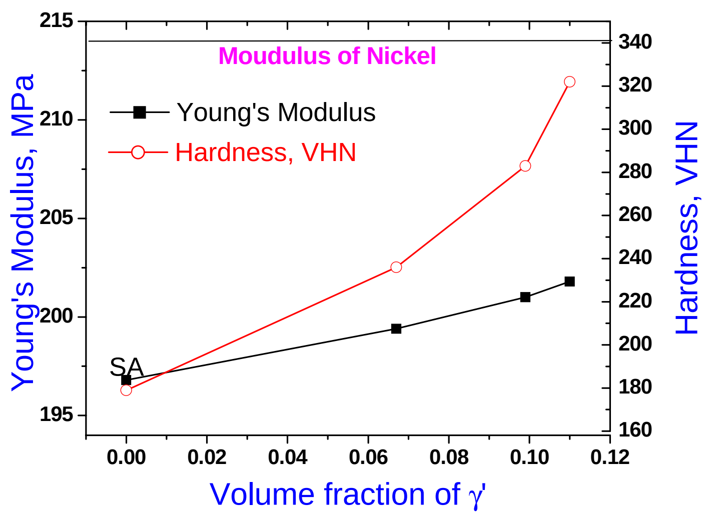

Fig. 2. Variation in Young's modulus with volume fraction of γ' in Nimonic PE 16. Modulus of pure nickel is also shown for direct comparison.

Young's modulus of these nickel base intermetallic precipitates is reported to be in the range of 180-185 GPa [8, 9]. This clearly indicates that Young's modulus of these nickel base intermetallic phases is lower than that of the nickel and the nickel base alloys. Hence, it can be deduced that increase in the Young's modulus of nickel base alloys upon precipitation of intermetallic phases is not governed by the modulus of these intermetallic phases as such. Further, due to the strain in elastic range, the maximum change in modulus of the alloy is reported to be less than about 1 % only [10], i.e. much lower than the maximum change (~6 %) observed upon precipitation of intermetallic phases in service exposed condition. This clearly indicates that the first two factors, i.e. modulus of either the intermetallic precipitates or the interface is not the prime factor in influencing the modulus of nickel base superalloys upon precipitation.

It can be seen very clearly from Figs. 1 and 2 that alloying of various elements to form the nickel base alloys decreases the Young's modulus of the matrix substantially. Hence, Young's modulus of the alloy is expected to increase upon precipitation of the intermetallic phases due to removal of the precipitation forming elements from the matrix. This clearly indicates that the change in the modulus due to precipitation of intermetallic phases in nickel base alloys is essentially governed by the change in the modulus of the matrix due to removal of precipitation forming elements, and not by the precipitated intermetallics or the matrix/intermetallic interface.

In light of the above understanding in nickel base superalloys, the major factor influencing the modulus of zirconium base alloys is also analyzed. Figure 3 shows the variation in Young's modulus of Zircoloy-2 upon ageing for 1 h at different temperatures. The increase in hardness upon ageing at intermediate temperatures is attributed to the precipitation of hard intermetallic phases such as $Zr_2(Ni,Fe)$ and $Zr(Cr,Fe)_2$. Contrary to the nickel base alloys, the precipitation of intermetallic phases is accompanied by a decrease in Young's modulus of zirconium base alloy. Figure 3 also shows the Young's modulus of pure zirconium [11]. It can be seen in this figure that unlike nickel base alloys, the Young's modulus of Zircoloy-2 is found to be higher than that of the base metal, i.e. zirconium. Based on the understanding in nickel base alloys, it is expected that, as the addition of alloying elements increases the modulus of the zirconium base alloys, the precipitation of intermetallic phases should lead to decrease in the modulus due to depletion of these elements from the matrix. This is in line with the experimental results that the precipitation of intermetallic phases decreases the modulus of Zircoloy-2. This indicated that in zirconium base alloys also the change in the modulus due to precipitation of intermetallic phases is essentially governed by the change in the modulus of the matrix due to removal of precipitation forming elements.

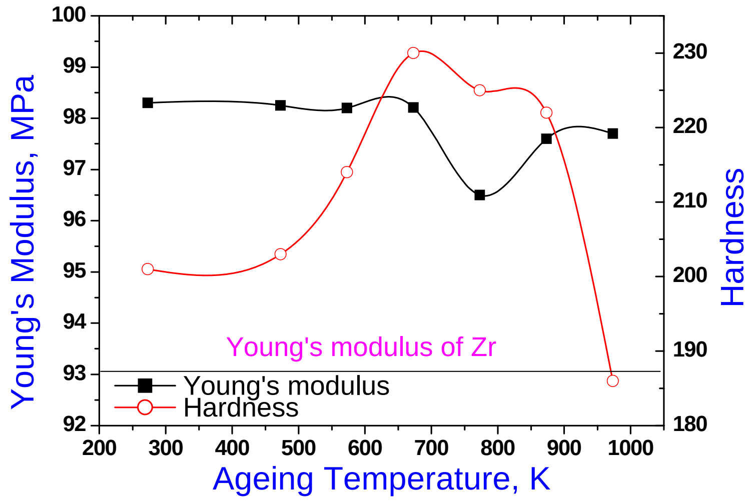

Fig. 3. Variations in Young's modulus and hardness with ageing temperature in Zircoloy-2. Young's modulus of pure zirconium is also shown for direct comparison.

4.0 Conclusion

The present study indicated that precipitation of intermetallics phases leads to increase in modulus of nickel base alloys, whereas decrease in modulus of zirconium base alloy. The study indicated that change in the modulus due to precipitation of intermetallic phases in nickel and zirconium base alloys is essentially governed by the change in the modulus of the matrix due to removal of precipitation forming elements, and not by the modulus of the precipitated intermetallics or the matrix/intermetallic precipitate interface.

Acknowledgements

We are thankful to Mrs. Vani Shankar, Dr. P. Palanichamy and Dr. K. Bhanu Sankara Rao for providing various specimens and useful discussions. We are also thankful to Shri P. Kalyanasundaram, Associate Director, ITG, IGCAR, Kalpakkam for his cooperation.

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