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研究課題名（和文）Novel strengthening mechanisms of high-strength Ni-Fe-based superalloys

研究課題名（英文）Novel strengthening mechanisms of high-strength Ni-Fe-based superalloys

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研究成果の概要（和文）：High content of Fe addition in Ni-Fe-based superalloys not only decreases the production cost but still has better mechanical properties than some other Ni-based superalloys. Ni-Fe-based superalloys has been optimized according to the well studied novel strengthening mechanisms.

研究成果の学術的意義や社会的意義
This Ni-Fe-based superalloy with low cost, good workabilities, great creep ruptured life has been considered as the promising candidate materials for hot section components in advanced ultra-supercritical power plants to improve electricity-producing efficiency, reduce CO2 emission and fuel cost.

研究成果の概要（英文）：High content of Fe addition in Ni-Fe-based superalloys not only decreases the production cost but still has better mechanical properties than some other Ni-based superalloys. Related phycical prameters during the multi-Orowan looping process have been also studied. Ni-Fe-based superalloy has been optimized according to the well studied novel strengthening mechanisms and finally achieved better mechanical properteis.

研究分野：Structural material science and engineering

キーワード：Ni-Fe-based superalloy　L12 ordered precipitate　Orowan mechanism　Dislocation

１．研究開始当初の背景

In coal-fired power generation, advanced ultra-supercritical (A-USC) technology with an increased steam temperature of 700°C is considered to be the key technology for the realization of better efficiency and reducing CO_2 emissions and fuel costs. The creep rupture strength requirement is a rupture life of 10^5 h at 700°C/100MPa. Materials widely used in 600°C USC technology do not have sufficient creep or oxidation resistance and could not perform well in harsh 700°C A-USC environments. Ni-based superalloys have satisfied the requirements, but high cost and poor workability for large components limited their application. Then, Ni-Fe-based superalloys with the addition of Fe (10-60wt.%) have been developed to make good workability and low cost. The typical microstructure of Ni-Fe-based superalloys is mainly composed of fcc γ matrix and dispersion of ordered $L1_2$ γ′ precipitates. Those γ′ precipitates act as obstacles to the glide of the dislocations and thus reduce their mobility. The strengthening depends on how dislocations interact with γ′ precipitates, which relies on the pinning of dislocations. Many investigations have studied the Orowan looping strengthening mechanisms but only focused on a single Orowan loop surrounding the precipitate. However, there are few studies about direct TEM observation of the double or more dislocation loops. The formation and strengthening mechanism of double Orowan looping processes in precipitation-strengthened alloys are still unclear.

２．研究の目的

This study aims to investigate the formation condition of double Orowan looping processes by controlling the γ′ precipitates characteristics, e.g., composition, size, volume fraction, etc. by changing composition and heat treatment methods. The strengthening effect is also expected to achieve based on the analysis results of experiments and numerical simulations after controlling the appearance of double Orowan loops.

３．研究の方法

During alloy preparation, series alloys have been designed with nominal chemical composition in wt%, 25–45 Fe, 15–20 Cr, 0.3–1.0 Mo, 2.5–3.5 (Ti + Al), 0.1–0.3 (C + B + P + Si), and the balance Ni. These Ni-Fe-based alloy cast ingots were prepared via vacuum induction melting and then homogenized at 1200 °C for 24 h. Heat treatment processes consisting of solid solution and aging heat treatments have been conducted to get various microstructural characteristics, such as size, and volume fraction of the γ′ precipitates. Tensile tests were conducted at 22 °C, 700 °C, and 750 °C to characterize the tensile properties and tensile deformation behaviors. Creep tests were also performed around 700°C with various stress, which could cause different resolved shear stress to make dislocation by passing the γ′ precipitates in terms of Orowan looping. The numerical simulation gave theoretical guidance for controlling the γ′ precipitation behaviors and understanding the interactions between the γ′ precipitates and dislocations. Series alloys have finally been well-optimized according to the dominant strengthening mechanisms.

４．研究成果

Fig.1 shows the developed Ni-Fe-based alloy with promising properties through controlling the alloy composition, heat treatment processes (solid solution and aging heat treatments) containing appropriate size and volume fraction of the γ′ precipitates. This alloy with a volume fraction of γ′ precipitates around 20% displays good yield strength around 700Mpa at 700°C. The predominant deformation behaviors in the grain interiors were planar slip and γ′ precipitate shearing by dislocation pairs at room temperature, Orowan, and dislocation shearing mechanisms at 700°C and 750°C, respectively.

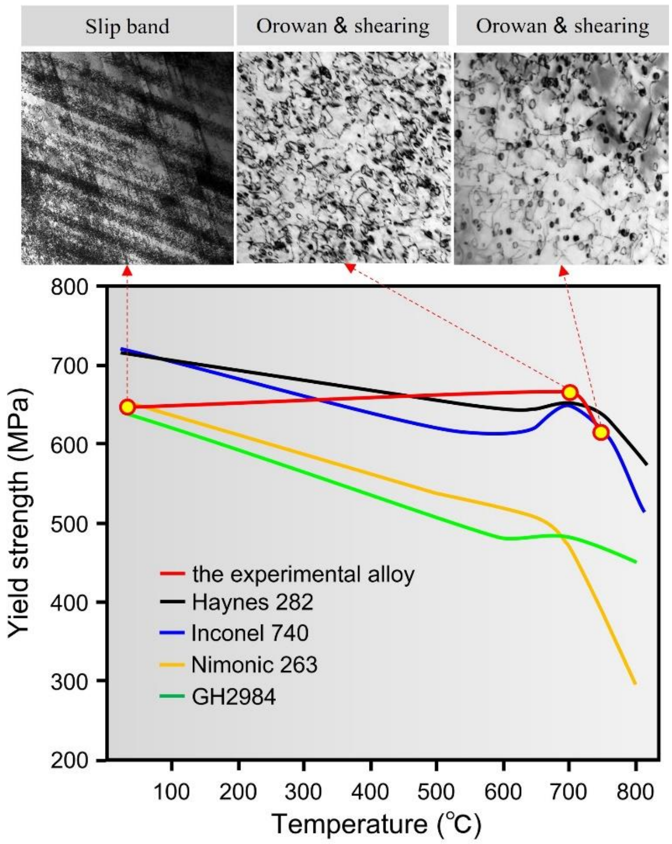

Fig.1 The yield strength as a function of the temperature of the developed Ni-Fe-based alloy and other Ni-based/Ni-Fe-based alloys. The predominant deformation behaviors in terms of dislocations interact with γ′ precipitates at various temperatures.

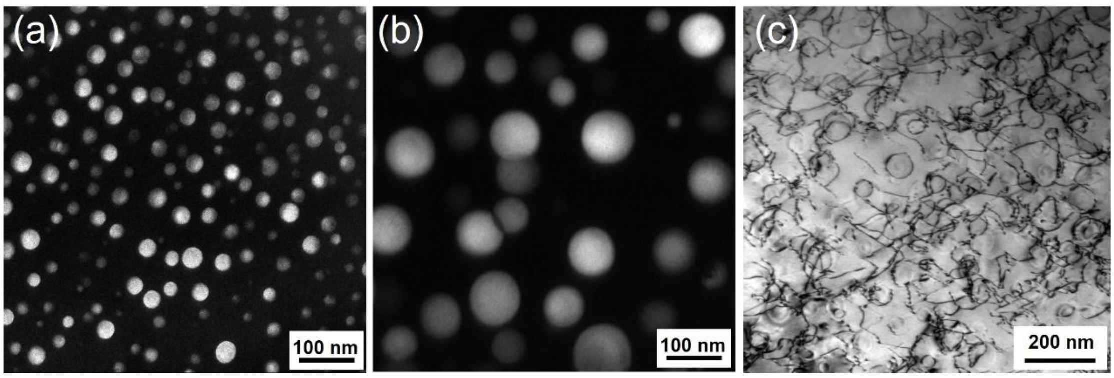

Fig.2 (a) and (b) TEM dark field images of γ′ precipitate after heat treatment and creep test at 700°C 150MPa, respectively. (c) Creep deformation microstructure consists of Orowan loops around the γ′ precipitates

Fig.2 (a) and (b) show the TEM dark field images of the γ′ precipitate before creep tests and after creep tests at 700°C 150MPa, respectively. Fig.2 (c) shows the TEM bright field image of dislocation interactions with γ′ precipitates. Single Orowan loops can be found obviously. In addition, the dislocation density is relatively high enough to glide in the matrix. The possibility of a double Orowan looping process is relatively high and some of them have been accomplished leaving double or more dislocation loops. The creep rupture life has been predicated using the Karson-Miller method, which satisfies the property requirement of 100,000 h creep strength greater than 100 MPa at 700°C for the hot section components application in 700°C class A-USC power plants.

The critical size of γ′ precipitates can be calculated as follows:

For Orowan looping:

$$\tau_o = 0.9 + \frac{[\ln(2\pi r/b)]^{3/2}}{[\ln(L/b)]^{1/2}}\left[\frac{K}{b(L-(\pi/2)r)}\right] \tag{1}$$

For precipitates shearing:

$$\tau_s = \frac{\gamma_{APB}}{2b}\left[A_1\left(\frac{\gamma_{APB} r f}{T_L}\right)^{1/2} + A_2 f\right] \times (1 + C_{SL}\eta_{SL}) \tag{2}$$

Where $K = (Gb^2)/[2\pi(1-\nu)]$ being the pre-logarithmic line tension factor of a straight edge dislocation. τ_o and τ_s are the critical resolved shear stress for Orowan looping and precipitate shearing, respectively. C_{SL} and η_{SL} represent one empirical constant and the normalized particle depth in the theory of Schwarz and Labusc, r is the mean precipitate radius, b is the Burgers vector, T_L is the dislocation line tension, A_1 and A_2 are fitting coefficients. Taking γ_{APB} =0.12Jm^{-2}, b=0.25 nm, f =0.2, G=60 GPa, the critical γ′ precipitate size for the dislocation transition from shearing to bowing is close to 30nm, consistent with the experimental result, and feasible for the multi-Orowan looping processes.

Three-dimensional discrete dislocation dynamics (3D-DDD) simulations of the interaction between a single dislocation source and the second phase shows that the closer the slip plane is to the center of the second-phase grains, the higher the yield stress and the higher the subsequent strain hardening rate. According to the simulation of the interaction between dislocation sources in different slip systems and the second phase, the higher the Schmid factor of the slip system, the lower the yield stress, and the lower the subsequent strain hardening rate. The dislocation motion states in the slip system are similar. The simulation of the interaction between multiple dislocations and the second phase found that, compared with the unit dislocation model, the yield stress and strain hardening rate of the multiple dislocation model were the lowest. In this study, 3D-DDD simulations were carried out on the interaction between dislocations and single particles, and the interaction between dislocation and multiple particles is worthy of further exploration, which is affected by factors such as particle size, particle distance, and particle volume fraction. There are still many microstructural parameters that can be adjusted, and the mechanism is more complex.

５．主な発表論文等

〔雑誌論文〕　計4件（うち査読付論文　1件／うち国際共著　1件／うちオープンアクセス　0件）

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３．雑誌名 Acta Materialia	６．最初と最後の頁 117487～117487
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.actamat.2021.117487	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

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掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/met12091425	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

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Sun Fei、Ogawa Toshio、Adachi Yoshitaka、Sato Kazuhisa、Takagi Shunya、Miyamoto Goro、Suzuki Asuka、Yamanaka Akinori、Nakada Nobuo、Ishimoto Takuya、Nakano Takayoshi、Koizumi Yuichiro	64
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掲載論文のDOI（デジタルオブジェクト識別子） 10.2320/matertrans.MT-ME2022004	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

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〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関