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Enhanced strength at intermediate temperatures in a Ni-base disk superalloy with high Co addition

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ABSTRACT

Influence of high Co addition, i.e. 15–30 wt%, on the compressive yield strength of a Ni-base disk superalloy (U720Li) has been investigated from room temperature to 1000 °C. It is found that Co addition has no obvious effect on the yield strength below 650 °C, but significantly increases the yield strength at 650–800 °C if Co content is below 25 wt%. The microstructure observations indicate that high Co addition up to 30 wt% has no significant effect on the phase constituent, but affects the size of secondary γ′. The deformation mechanisms are discussed according to a newly developed model. It is suggested that high Co addition induces the transition of deformation mechanisms from dislocation pairs cutting to SF shearing and/or deformation twinning, which may be responsible for the enhanced strength at intermediate temperatures.

1. Introduction

Ni-base superalloys are widely used in aircraft engines and land-base gas turbines, owing to the unique high temperature mechanical properties. In these alloys, Ni_3Al type γ′ precipitates with an $L1_2$ structure are dispersed in the disordered solid solution face centered cubic (fcc) γ matrix. For advanced disk superalloys, the service temperature is usually above 650 °C and sometimes close to 800 °C because of the design of high efficiency turbines. Therefore, the mechanical properties of disk superalloys at intermediate temperatures, i.e. 650–800 °C, are of great importance.

Alloying elements are well known to greatly affect the mechanical properties of alloys. Co has been identified as a strategic element. Hence, fully understanding the roles of Co in superalloys is necessary for reasonable consumption. Several authors reviewed the Co effects in both single crystal superalloys and polycrystalline disk superalloys [1–3]. In single Ni-base superalloys, it is believed that Co addition can suppress the formation of TCP phase and improve the stress-rupture life [4–6]. The Co content in most of single crystal superalloys is less than 10 wt% [7]. Modern disk superalloys, such as U720Li [8], Rene 88DT [9], 718Plus [10], and ME3 [11], usually contain 10–20 wt% Co. Tien et al. used their empirical equation to predict that the effect of Co addition on the yield stress, a major concern for disk superalloys, is not large [1]. However, up to date, there have been limited experimental investigations of the effect of Co on the strength [12–15]. It is commonly concluded that Co addition has no significant influence on the yield strength of superalloys at both ambient and intermediate temperatures [1,2]. For example, Mauer et al. reported that there is only about 4% improvement of the yield strength at room temperature (RT) in Waspaloy alloy by replacing Ni with Co up to 13.25 wt%, whereas no essentially effect on the yield strength at 538 °C [12]. More recently, Xu et al. [16] studied the effects of Co and Ti additions in a Udimet 710 alloy. The Co content was varied from 13.4 wt% to 48.2 wt%, and the strength increased with increasing Co and Ti content. In their report, the Ti content was simultaneously changed and the third phase, eta phase, existed in all modified alloys, which makes the explanation more complicated [16]. Therefore, the Co effect on strength, especially high Co content in disk superalloys, needs further investigation to obtain a better understanding.

Novel cast and wrought (C&W) TMW® disk superalloys have been developed at National Institute for Materials Science, Japan [17–22]. These new alloys exhibit higher temperature capability and better overall mechanical properties than current commercial C&W disk alloys. Base on the systematic investigations, we have proposed a new method, twin strengthening, to strengthen advanced superalloys [23,24]. In the previous studies, the twin structures were attributed to low stacking fault energy (SFE). Furthermore, Co was found to effectively decrease the SFE with an appropriate content [25]. The TMW alloys contain higher Co and Ti content than U720Li alloy. Co in TMW-4M3 is increased up to 25.0 wt% (15.0 wt% in U720Li), apparently higher than the

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commonly accepted level. The content of Cr, Mo and W is slightly different. Therefore, the influence of other alloying elements cannot be excluded completely. In other words, the effect of high Co addition in TMW alloys needs further clarification in order to fully explore their mechanical performance.

In this study, the influence of high Co addition, in the range of 15–30 wt%, on the compressive yield strength of U720Li and its modified alloys from RT to 1000 °C has been investigated. The deformation mechanisms are discussed using a newly developed model.

2. Experiment

U720Li was selected as a base alloy. By replacing Ni, the Co addition in U720Li was gradually increased from 15 wt% to 30 wt%. The alloys were prepared by arc-melting. Then, the as-cast ingots were homogenized at 1200 °C to eliminate the dendritic microstructures. Aging treatments were carried out as follows: 650 °C/24 h/air cooling+760 °C/16 h/air cooling. The cylindrical specimens of 3 mm in diameter and 6 mm in length were cut from the ingots by electric discharge machine. Compressive tests were conducted at a strain rate of $2.5 \times 10^{-4}\ s^{-1}$ in the temperature range of RT to 1000 °C. Testing was stopped after yielding point and a total strain of around 2.0%. Transmission electron microscopy (TEM) disks were cut from the tested samples perpendicular to compressive axis. These disks were manually ground to 50 μm and perforated by twin-jet electro-polisher at 40 V/18 mA and −10 °C. The electrolyte consisted of 225 ml acetic acid, 225 ml butylcellosolve and 50 ml perchloric acid. The deformation microstructures were investigated using a Tecnai 20 microscope operated at 200 kV.

Table 1
The nominal chemical compositions of U720Li, modified alloys and TMW-4M3 (wt%).

Alloys	Ni	Cr	Mo	W	Co	Ti	Al	C	B	Zr	V_f (%)[a]
U720Li	Bal.	16	3	1.3	15	5	2.5	0.02	0.02	0.03	44.8
M1	Bal.	16	3	1.3	20	5	2.5	0.02	0.02	0.03	44.8
M2	Bal.	16	3	1.3	25	5	2.5	0.02	0.02	0.03	44.5
M3	Bal.	16	3	1.3	30	5	2.5	0.02	0.02	0.03	44.1
TMW-4M3	Bal.	13.5	2.8	1.2	25	6.2	2.3	0.02	0.02	0.03	49.5

[a] V_f denotes the total volume fraction of γ′ precipitates at 760 °C.

3. Results and discussion

3.1. Chemical compositions of the alloys

The nominal chemical compositions of U720Li and modified alloys are given in Table 1. The Co addition was varied from 15 wt% to 30 wt%. For convenient comparison, the composition of TMW-4M3 is also listed. The total volume fraction of γ′ precipitates (V_f) at 760 °C was calculated using a Thermal-Calc program with a Ni-RUMN database and is also included in Table 1. The variation of V_f with Co content is less than 1.0%, implying that Co addition within 15–30 wt% has negligible effect on the V_f.

3.2. Yield strength vs. Co content

The yield strengths as a function of Co content at different temperatures are plotted in Fig. 1. At RT and 650 °C (Fig. 1(a)), four alloys had comparable yield strength, which indicates that Co content has no obvious effect on the strength below 650 °C. This is consistent with references [1,12–14]. At 750 and 800 °C (Fig. 1(b) and (c)), a significant peak strength was observed at approximately 25 wt% Co. A further addition of Co to 30 wt% decreased the strength. Comparing the strength of M2 (25 wt% Co) and M3 (30 wt% Co) at 800 °C, the former had nearly 25% higher strength than the latter. These results show that higher Co content does strongly affect the yield strength at intermediate temperatures. Among TMW alloys, TMW-4M3 has 25 wt% Co and possesses the highest tensile yield strength at intermediate temperatures [17]. Higher yield strength at intermediate temperatures is always desired for applications of advanced disk

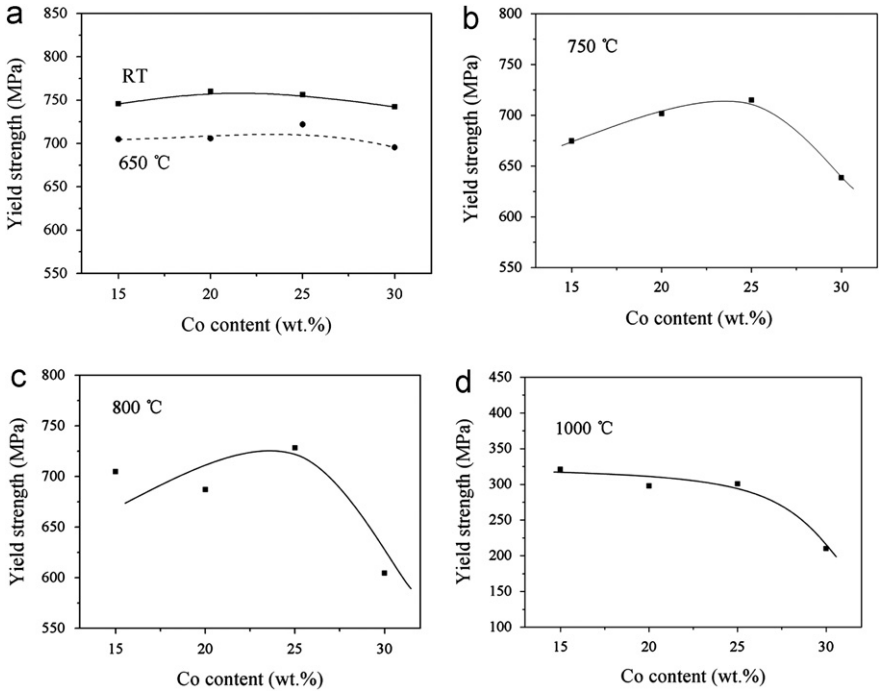

Fig. 1. Yield strength as a function of Co content at (a) RT and 650 °C, (b) 750 °C, (c) 800 °C, and (d) 1000 °C.