Carbon Addition and Temperature-Dependent Tensile Properties of a Low-Cost 3rd-Generation Ni-Based Single Crystal Superalloy

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Abstract
Doping with an appropriate carbon is anticipated to balance the mechanical properties and castability of Ni-based single crystal (SX) superalloys. This work examined the effects of carbon content on tensile properties of a novel Ni-based low-cost third-generation SX superalloy, at 760 °C and 1120 °C. The results show that increasing carbon content improved the strength and plasticity at 760 °C. However, the elevated temperature to 1120 °C caused a loss in strength and plasticity. With the Vickers hardness and high-resolution X-ray diffraction tests, it was confirmed that a minor addition of carbon could improve the solid solution strength and interface strength of SX superalloy. However, the high-temperature strength of high-carbon alloys will be compromised for the large consumption of refractory elements by interdendritic MC carbides, although the blocky M_6C carbides could provide an additional hindrance to dislocation motion. Regarding the macroscopic deformability, EBSD confirms that MC carbides could apply as an obstacle to impede the rapid shear decohesion at 760 °C, nevertheless, the severe stress concentration and deformation incompatibility near MC carbides would promote microcrack initiation and propagation behaviors at 1120 °C. Overall, future compositional optimization should focus on reducing the formation of Ta-enriched MC carbides to minimize refractory element depletion and deformability reduction at high temperatures.
Keywords: Ni-base single crystal superalloys, carbon, tensile properties, carbides

Introduction
In Ni-based SX superalloys, the boundary strengthener carbon had been completely removed to obtain superior mechanical properties. Practical applications require SX superalloys with favorable castability to boost the qualification rate of turbine blades during manufacturing. Appropriate inclusion of carbon in advanced Ni-based SX superalloys is critical to limit the formation tendency of stray grain, recrystallization, and high-angle grains (HAG) [1, 2]. The effect of carbon addition on the mechanical properties of Ni-based SX superalloys has been extensively studied. However, these studies concentrated on the effects of carbon on the creep and fatigue properties of first and second-generation SX superalloys [3, 4]. Limited studies on the tensile properties of Ni-based SX superalloys as a function of carbon content can be found. Therefore, it is necessary to ascertain the effect of carbon addition on the tensile properties of the novel alloy to indicate its' further creep and fatigue properties.

In this work, we investigated the impact of temperature and carbon content on the tensile characteristics of a novel low-cost 3rd-generation Ni-based SX superalloy. The synergistic *carbon content & temperature* effects on tensile properties were highlighted, which could guide future carbon modifications and practical applications of this newly developed SX superalloy.

Experimental procedure
The chemical composition of the novel low-cost 3rd-generation Ni-based SX superalloys with three different carbon content is given in Table 1. Master ingots were prepared from pure metals in a vacuum induction melting (ZG-0.01). Single bars with dimensions ϕ16×220 mm were then produced using the selecting crystal method in a vacuum directional solidification furnace (HRS, ZGD-15), at a withdrawal rate of 6 mm/min. From these bars, only single rods with an orientation deviation [001] within 10° were wire-cut into ϕ16×60 mm rods for subsequent heat treatment. Here, the same high-temperature solution and two-step aging heat treatments were carried out for the three experimental alloys as follows:
1320~1325℃/1h + 1325~1330℃/3h + 1335~1340℃/4h (A.C.) → 1100℃/6h (A.C.) + 870℃/24 h (A.C.).

Table 1. Composition of Alloy 0C, 0.045C and 0.85C, wt.%

Alloys	C	Re	Cr	Co	Mo+W+Ta	Al	Ni
0C	0	2.93	4.56	7.95	14.76	5.70	Bal.
0.045C	0.048	2.93	4.53	7.92	14.80	5.68	Bal.
0.085C	0.083	2.91	4.51	8.03	14.73	5.72	Bal.

Result and discussion
Tensile properties
The engineering stress-strain (ε-σ) curves of the three alloys at 760 °C and 1120 °C were displayed in Fig.1. At 760 °C, the ε-σ curves were almost indistinguishable from each other, and all of them exhibited insignificant yielding phenomena. While differences appeared at 1120 °C, especially for the ultimate strength and rupture elongation. Table 2 compares the strength and plasticity of three alloys at 760 °C and 1120 °C. It could be noticed that the yield strength (YS) and ultimate tensile strength (UTS) at 760 °C increased slightly with increasing carbon

content. Particularly, the plasticity of alloy 0.085C outperformed about 60% than that of alloy 0C and 0.045C. At 1120 °C, YS gradually decreased from 313 MPa of alloy 0C to 285 MPa of alloy 0.085C. Simultaneously, plasticity decreased significantly with increasing carbon addition.

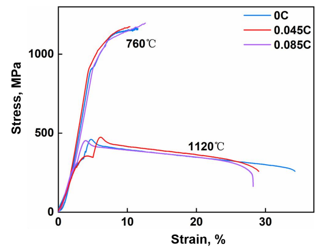

Fig. 1 Stress-strain curves of three alloys at 760 ℃ and 1120℃

Table 2 Strength (YS and UTS, MPa) and plasticity (δ and A, %) of Alloy 0C, 0.045C and 0.085C.

Alloys	760 ℃				1120 ℃			
	YS	UTS	δ	Z	YS	UTS	δ	Z
0C	921	1165	4	5.5	313	459	34	50
0.045C	938	1174	4.8	4.5	290	475	24	42
0.085C	944	1196	8	9.5	285	452	27	36

Carbide effects

The influences of carbon addition on tensile properties were discussed in terms of the intrinsic microscopic resistance to dislocation movements and deformability to macroscopic damage accumulation. It was found that the solid solution strength and interface strength increased with increasing carbon content, as confirmed by HV and HR-XRD tests. With TEM characterization, the precipitation of blocky M_6C carbides was found to apply as a hindrance to dislocation movement. However, the high-temperature strength was severely weakened due to the massive consumption of refractory elements caused by the formation of interdendritic Ta-enriched MC carbides. Here, the effects of MC carbides on macroscopic deformability were examined via electronic backscatter detection technology (EBSD). At 760 ℃, extensive secondary slip bands were observed upon MC carbides, nevertheless, only a modest amount of slip bands were detected at locations below those carbides (Fig.2(a)). At 1120℃, severe recrystallization occurred in regions containing large MC carbides, while the areas containing small carbide particles still showed severe crystal rotation (Fig.2(b)). Summarily, we could assume that the improved plasticity at 760 °C originated from the attenuating slip band extension, whilst the reduced plasticity at 1120 °C was generated by collectively promoting microcracks initiation and propagation near interdendritic MC carbides.

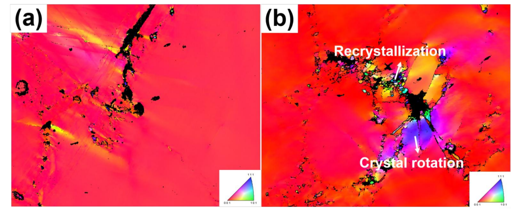

Fig. 2 EBSD-IPF maps in interdendritic region of alloy 0.085C at (a) 760 ℃, (b) 1120℃.

Conclusion

Minor carbon addition could improve the strength of the novel low-cost third-generation SX superalloy by enhancing its solid solution strength and interface strength. However, the formation of interdendritic MC carbides would cause massive consumption of refractory elements, thus leading to the strength slump at high temperatures, even though blocky M_6C carbides provided additional hindrance for dislocation movement. As for plasticity, the existence of MC carbides could hinder the extension of slip bands at 760 ℃, leading to an increase in plasticity. Nevertheless, those MC carbides would facilitate microcracks initiation and propagation behavior, which resulted in a drastic decrease in plasticity at 1120 ℃. Therefore, future compositional optimization should focus on reducing the formation of MC carbides to diminish the strength loss and deformation incompatibility at high temperatures.

References

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