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Creep properties beyond 1100 °C and microstructure of Co–Re–Cr alloys

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ABSTRACT

The melting point of a novel Co–17Re–23Cr alloy (numbers given in at.%) could be increased by 250 °C as compared to established Ni-based superalloys, by optimising the content of Re. Samples were produced by vacuum arc-melting in order to evaluate the creep behaviour at temperatures beyond 1100 °C and for microstructural analysis. Three alloys (the Co–17Re–23Cr-based material, and the carbide strengthened alloys Co–17Re–23Cr–2.6C and Co–17Re–23Cr–2.6C–1.2Ta) were investigated. Creep properties, especially the minimum creep rate and the Larson–Miller plots, were compared. The Co–17Re–23Cr–2.6C–1.2Ta alloy has a higher minimum creep rate than Co–17Re–23Cr at 1200 °C but it has a lower minimum creep rate than Co–17Re–23Cr at 1100 °C. TaC coarsening, detected via transmission electron microscope (TEM) measurements may explain this effect. The overall creep behaviour of Co–17Re–23Cr–2.6C at 1200 °C is better than that of Co–17Re–23Cr–2.6C–1.2Ta, but worse than that of Co–17Re–23Cr.

Microstructural investigations by scanning electron microscopy and TEM reveal a hexagonal closed-packed (hcp) matrix and σ-phases. The microhardness of the σ-phase was about 1570 HV (load: 1 g) and around 800 HV for the matrix. Pores and cracks occur along the brittle σ-phases and grain boundaries in the Co–Re–Cr alloys. A Norton exponent *n* in between 1.4 and 3.0 points to grain boundary dominated creep mechanisms.

1. Introduction

Ni-based superalloys are currently the materials of choice for the hottest and most severely stressed parts in stationary gas turbines and aero engines. However, their operating temperature is limited to about 1100 °C due to dissolution of the γï precipitates. Promising materials to handle higher operating temperatures are for example molybdenum silicides [1–3] and Pt-based alloys [4,5], which attracted interest in the last decade.

Recently Rösler et al. [6] drew attention to the Co–Re alloy system. They pointed out that Re is known to be an important alloying element in Ni-based superalloys since the early 1980s, the limited solubility of Re in Ni prevents the full exploitation of the Re strengthening effect. In contrast to the low solubility in Ni-based alloys, Re is completely miscible with Co (Fig. 1). This may allow to tune the properties of Co–Re-alloys as required and hence to find a suitable balance between toughness and ductility on the one hand, and strength at high temperatures beyond the capabilities of current Ni-based superalloys on the other hand [6].

Conventional Co-based superalloys like X-40 show favourable thermal shock and fatigue properties. Furthermore, components made of Co-based alloys can be effortlessly maintained due to its weldability and possible braze repair of cracks [8]. Up to 30 wt.% Cr are commonly added for adequate corrosion and oxidation resistance. A content of about 10 wt.% of Ni guarantees that these alloys have a face centred cubic crystal structure. Minor additions of W, Ta, C and other elements result in solid solution strengthening and dispersion or precipitation strengthening by carbide formation [9]. However, the inferior mechanical properties as compared to the γ′ strengthened Ni-based superalloys may be the reason for limited research activities on Co-based alloys over the last decades. Only recently Sato et al. [10] and Ping et al. [11] reported a new way of γ′ strengthening in Co-based alloys.

This publication presents the creep properties and microstructure of new Co-based alloys with high Re and Cr concentrations and minor additions of C and Ta and compares them to the conventional Co-based alloy X-40. As stated in the literature [13] Re is added in order to increase the melting point and the high temper-

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Table 1
Investigated Co–Re–Cr alloys with their alloy composition in at.%, and further treatments.

Designation	Composition (at.%)	HIP at 1400 °C/3 h/200 MPa (Ar)	Heat treatment in vacuum
CoReCr	Co–17Re–23Cr	No	1350 °C/5 h + 1400 °C/5 h + 1450 °C/5 h
CoReCrC	Co–17Re–23Cr–2.6C	Done	1350 °C/5 h + 1400 °C/5 h + 1450 °C/5 h
CoReCrCTa	Co–17Re–23Cr–2.6C–1.2Ta	Done	1350 °C/7.5 h + 1400 °C/7.5 h
X-40	Co–28.5Cr–9.9Ni–2.1Si–1.1Mn–2.4W–2.1Fe–2.4C	No	1200 °C/8 h + 800 °C/24 h/AC

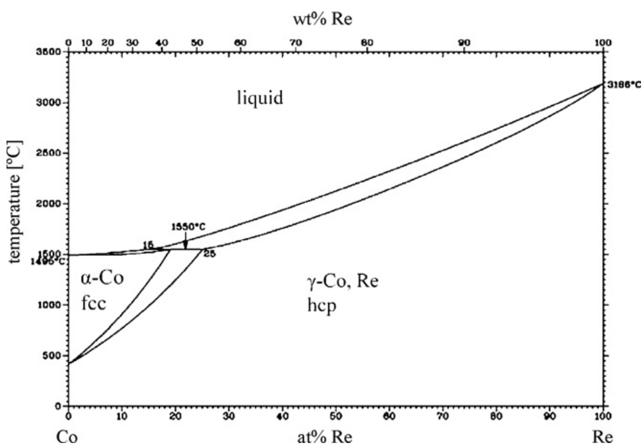

Fig. 1. Binary phase diagram of Co and Re [7].

ature strength. The oxidation resistance is improved by adding Cr [14]. C and Ta are added to assist carbide formation like they would in conventional Co-based superalloys.

2. Experimental

2.1. Materials

The three investigated alloys, Co–17Re–23Cr, Co–17Re–23Cr–2.6C and Co–17Re–23Cr–2.6C–1.2Ta (numbers given in at.%), were arc melted on a copper chill plate and poured into a water-cooled copper mould. Some of the 70 mm × 10 mm × 10 mm bar ingots were compacted in a hot isostatic press (HIP) at 1400 °C and 200 MPa in argon atmosphere for 3 h [6]. The commercial Co-based alloy X-40 was manufactured in the same way to serve as a reference. The composition and the labelling of the alloys are listed in Table 1, along with additional treatments.

2.2. Creep testing

Creep tests were performed using two different facilities. Firstly, the standard creep testing with 70 mm long samples is announced. Specimens were eroded out of cast ingots by wire electrical discharge machining (EDM). The geometry of the creep specimens has four small ridges at the specimens centre. These ridges mark the gauge section with a volume of 6 mm × 3 mm × 1 mm (Fig. 2). The ridges are necessary for the creep strain measurements with a proprietary video extensometer [15]. Specimens were tested as-eroded. The so-called recast layer of about 20 μm thickness was neglected in the stress calculations. The broadened endings of the specimens were ground to guarantee good contact to the grips.

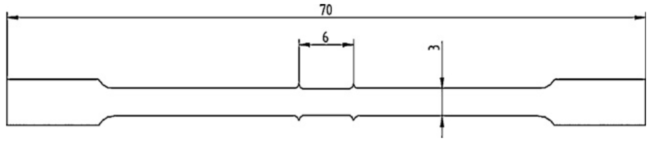

Fig. 2. Geometry of specimens for standard tension creep tests. The thickness is 1 mm. The gauge volume between the ridges is 6 mm × 3 mm × 1 mm.

The proprietary creep test devices [16] used in this study heat the specimens directly by an alternating current. High heating (~100 °C/s) and cooling (~50 °C/s) rates are possible. Constant load tensile creep tests were performed from 1100 °C up to 1250 °C under vacuum and at different stress levels (15–50 MPa), until rupture. A video extensometer measured continuously the creep strain with a relative accuracy below 10^{-3} [15,17]. Closed-loop temperature control was obtained with a S-type thermocouple (Pt/Pt–10% Rh). The thermocouple was spot welded onto the specimens next to the gauge section—above the two upper ridges. This avoids any influence on the creep deformation within the gauge section. All specimens ruptured between the ridges of the gauge section.

The temperature distribution over the specimen, heated to a nominal temperature of 1200 °C, was simulated by finite element modelling (FEM) with ANSYS (ANSYS 11.0, Flexlm, Ansys, Inc., USA). The difference between the hottest part of the creep specimen – in the middle – and the ridges marking the gauge length is about 8 °C according to the FEM simulation (Fig. 3). This temperature difference varies in practice, due to the welding spot size and its proper position. In each creep test the difference was precisely measured by a calibrated dual wavelength pyrometer (IGAR 12-LO, Impac Infrared GmbH, Germany). Both the pyrometer measurements and the FEM simulations showed a maximal temperature gradient of 8 °C between the middle of the specimen and the spot-welded thermocouple.

Secondly, miniature creep tests were carried out. In contrast to the standard creep tests their overall length of samples is 25 mm. The miniature creep tests were performed under a protective 95% Ar/5% H_2 atmosphere using a creep testing device of type Denison Mayes Group TC20 modified with a custom designed vacuum chamber. These tests are indicated as 'miniature creep tests' in the present publication. The precise sample geometry and further details of the measurement can be found in the literature [18–20].

2.3. Microstructure

The microstructure of the Co–Re–Cr alloys was analysed with scanning electron microscopes (SEM 1540EsB Cross Beam and LEO Gemini 1530 VP, Carl Zeiss AG, Germany).

TEM investigations in scanning mode were carried out on a Tecnai F20, FEI, microscope operated at 200 kV, equipped with a high

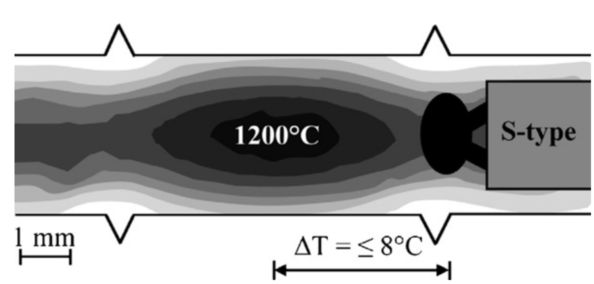

Fig. 3. The temperature distribution over the gauge length as simulated by FEM. The maximum temperature difference between the centre of the specimen and the tip of the thermocouple is 8 °C.