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Silicide precipitation strengthened TiAl

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Abstract

Precipitation of a titanium silicide Ti_5Si_3 was found to be beneficial to improvement of the creep resistance of a fully lamellar Ti–48Al–1.5Cr cast alloy without the sacrifice of tensile properties. The addition of 0.26–0.65 mol% Si generates fine precipitates less than 200 nm in size during aging at 900 °C for 5 h. The precipitates are effective obstacles to dislocation motion and raise the stress exponents of power law creep significantly. The specific creep strength of Si-containing alloys is better than that of a conventional Ni-base cast superalloy Inconel 713C at 800 °C for 10000 h.

Keywords: Silicon; Precipitation; Titanium; Aluminium

1. Introduction

Among various intermetallic compounds, TiAl has great potential as a high temperature structural material for the aerospace and automobile industries [1–3]. It possesses specific tensile and fatigue strengths at room temperature (RT) and elevated temperatures superior to those of conventional cast Ni-base superalloys such as Inconel 713C currently used for turbocharger turbine wheels [3]. Before replacing superalloys with TiAl, three major problems must be solved: the low ductility under 700 °C, and the poor oxidation resistance and insufficient creep strength both above 800 °C.

In the Ti–Al binary system, the highest RT ductility has been obtained for a non-stoichiometric composition of 48 mol% [4,5]. This microstructure is duplex consisting of $TiAl(\gamma)Ti_3Al(\alpha_2)$ lamellae dotted with γ grains [6]. The addition of Mn and Cr to γ-TiAl alloys has been found effective in improving the RT ductility [7,8]. The oxidation resistance of the alloys has been enhanced by alloying with Nb, Ta and Si [9,10].

Unfortunately, the ductile duplex alloy has low creep strength compared with fully lamellar alloys with large colonies [11]. Many attempts to improve the creep resistance of γ-TiAl alloys using conventional methods, solid solution, precipitation and composite strengthening [12,13], have been only partially successful.

Recently, researchers have demonstrated that the addition of Si improves the creep resistance significantly and titanium silicide precipitates were observed in creep test specimens [14,15].

Titanium silicide is a candidate strengthening dispersoid because of its higher stability. In this study, the effect of silicide precipitation on the RT tensile properties and the creep strength of TiAl was evaluated.

2. Experimental details

The chemical compositions of the investigated alloys are shown in Table 1. The Si-free alloy is a reference fully lamellar alloy containing Cr, which was designed

Table 1
Chemical compositions (in mole per cent) of the alloys

Alloy	Al	Cr	Si	C	O	N
Si free	47.6	1.6	<0.02	0.05	0.18	0.011
0.26 Si	47.7	1.7	0.26	0.03	0.14	0.008
0.65 Si	47.3	1.5	0.65	0.03	0.17	0.008

Balance Ti.

as a cast alloy by the authors. Originally no heat treatment was applied to the castings before service.

The three alloys were melted down in a special argon plasma skull furnace and then cast into 5 kg ingots 100 mm in diameter. From the ingots, 14 mm diameter round bars were cut out by electrodischarge machining. The aging for bars as cast was performed at 900 °C for 5 h, selected by preliminary testing.

The gages of tension and tensile creep test specimens were 8 mm diameter and 40 mm length and 6.35 mm diameter and 31.75 mm length respectively. All test were carried out in air at RT and elevated temperatures.

3. Results and discussion

3.1. Microstructures

Optical and scanning electron micrographs are shown in Fig. 1 of the three alloys as aged. The matrix was fully lamellar; $Ti_3Al(\alpha_2)$ is brighter than $TiAl(\gamma)$ in scanning electron backscattering images.

In the Si-containing alloys, precipitate skeletons were observed at the interdendritic region. They were greater in higher Si content alloys. The precipitates were identified as Ti_5Si_3-type titanium silicides chemically by energy-dispersive X-ray (EDX) analysis in situ

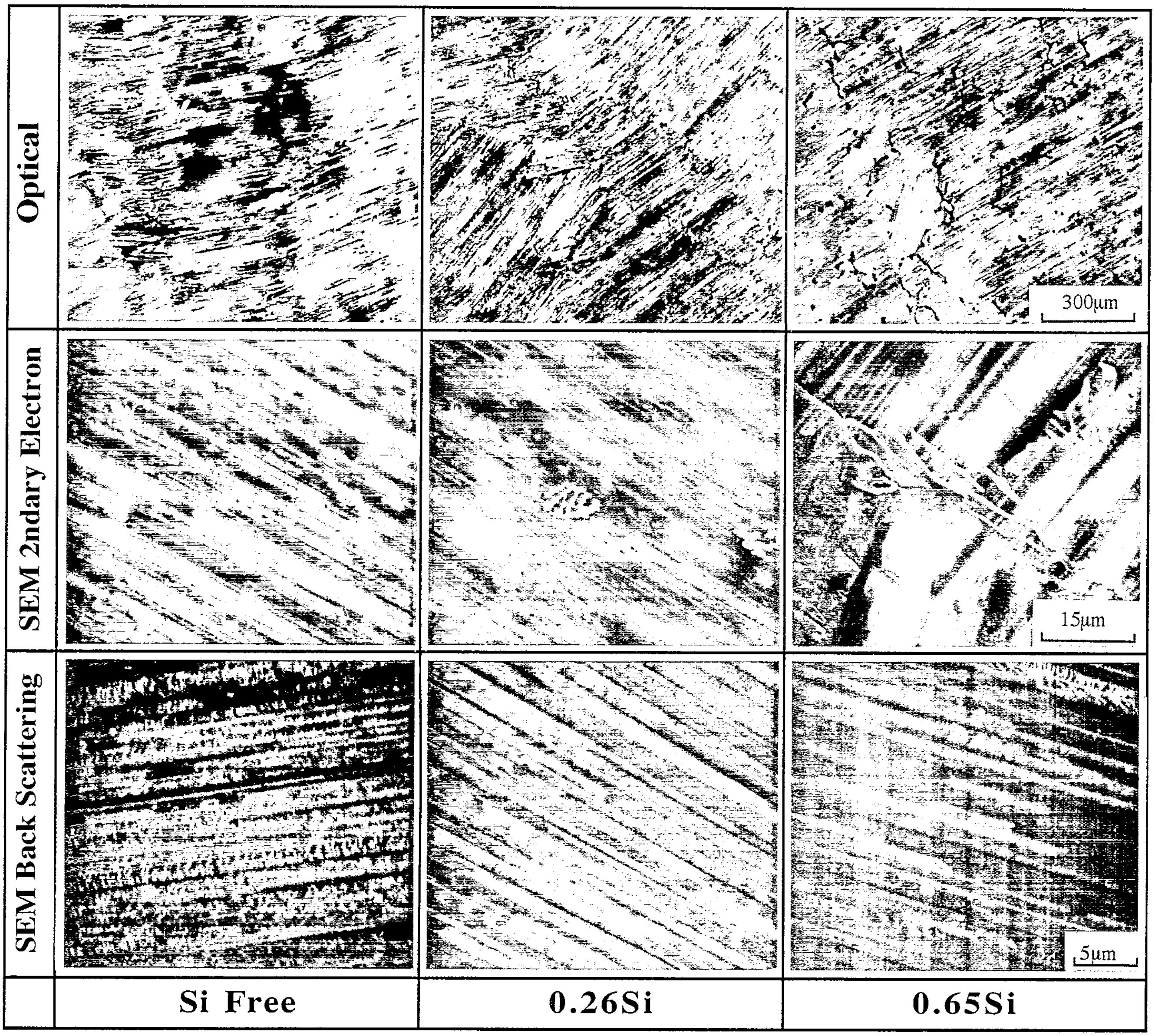

Fig. 1. Microstructures of samples as aged at 900 °C for 5 h; etchant 2 ml HF + 4 ml HNO_3 + 100 ml H_2O.

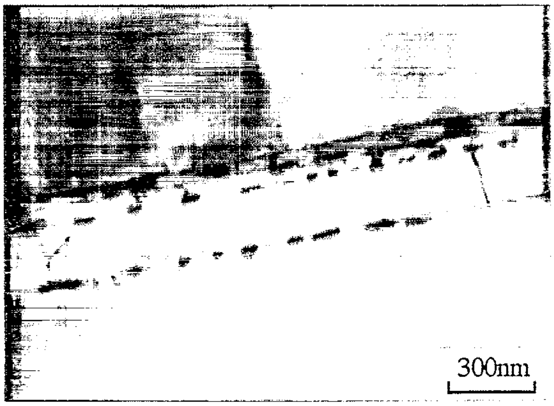

Fig. 2. TEM image of 0.65 Si alloy as aged at 900 °C for 5 h.

on the polished plane and also crystallographically by X-ray diffraction of particles extracted electrochemically. Because the precipitates were inherited from the cast structures, it was deduced that they precipitated during solidification through the following eutectic reaction

$$L \longrightarrow \beta + Ti_5Si_3$$

at the higher Si interdendritic regions supercooled constitutionally.

A transmission electron microscopy (TEM) image of the 0.65 Si alloy is shown in Fig. 2. Along the lamellar interfaces, very fine particles precipitated, which were

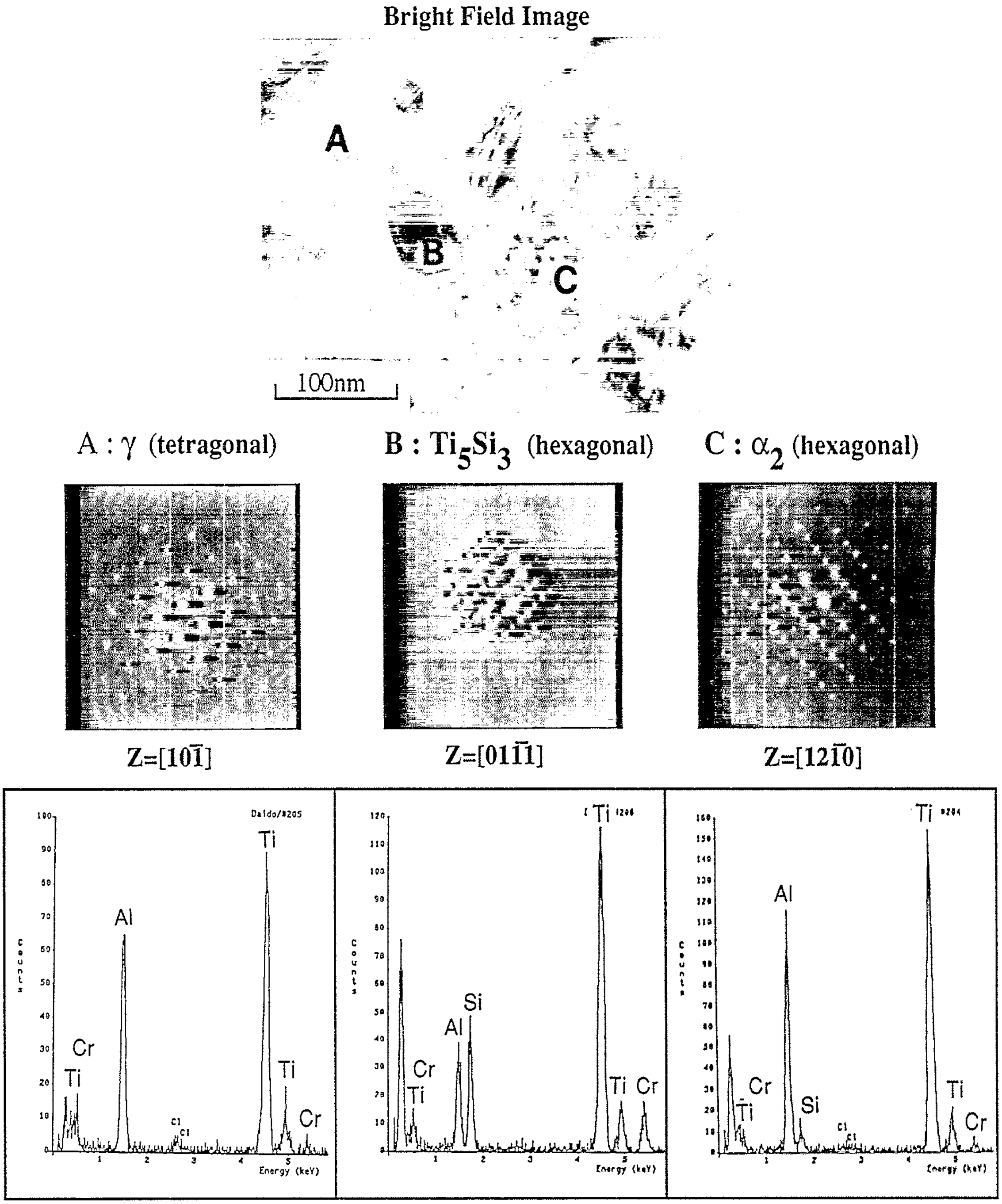

Fig. 3. Results of AEM analysis of 0.65 Si alloy.

not present in as-cast alloy. The results of AEM analysis are shown in Fig. 3. The bright field image depicts a precipitate B extended from the interface of two layers (A, C) into the core of the layer C. The precipitate was identified as Ti_5Si_3 again containing Al and Cr. The layers A and C were identified as γ and α_2 respectively. The latter was richer in Si than the former. The results imply that Ti_5Si_3 nucleated at the interface of γ and α_2 and grew in α_2. The aligned precipitates in γ, Fig. 2, suggest that they developed through the following eutectoid reaction:

$$\alpha_2 \rightarrow \gamma + Ti_5Si_3$$

A TEM image is shown in Fig. 4 of the 0.65 Si alloy after creep testing under 200 MPa at 800 °C for 1213 h. The dislocations in γ were pinned by the precipitates at lamellar boundaries and also bowed around them in γ. The image also shows that the Ti_5Si_3 precipitates acted as obstacles to dislocation motion equivalent to γ' in Ni-base or Y_2O_3 in mechanically alloyed oxide dispersion strengthened superalloys.

Another TEM image of the same alloy, Fig. 5, shows the precipitates in γ after creep. This demonstrates the ripening of precipitates during the creep test. It also suggests that the α_2 layer was thinned by consumption via the above mentioned eutectoid reaction: $\alpha_2 \rightarrow \gamma + Ti_5Si_3$.

3.2. Tensile properties

The proof stress and the elongation are shown in Fig. 6. From RT to 800 °C the precipitation did not increase the proof stress, which varied only with variation in the lamellar spacing [16].

The addition of 0.65 Si decreased the elongation slightly, while the addition of 0.26 Si did not degrade the ductility at all.

3.3. Creep properties

The typical creep curves for testing conditions of 200 MPa and 800 °C are shown in Fig. 7 obtained from the constant tension load test. They show three distinct stages: primary, steady state or minimum, and accelerating creep. The addition of Si decreased the primary creep strain and minimum creep rate and also increased the rupture life and the elongation to failure.

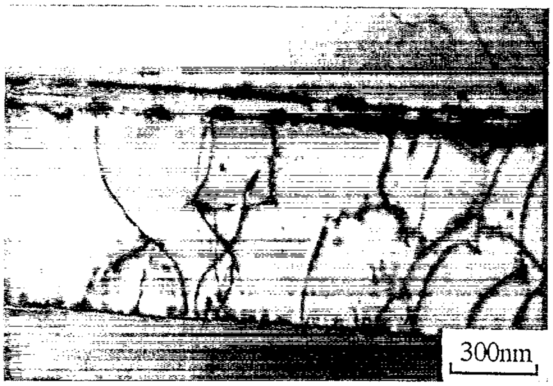

Fig. 4. TEM image of 0.65 Si alloy after creep under 200 MPa at 800 °C for 1213 h, showing pinning and bowing of dislocations.

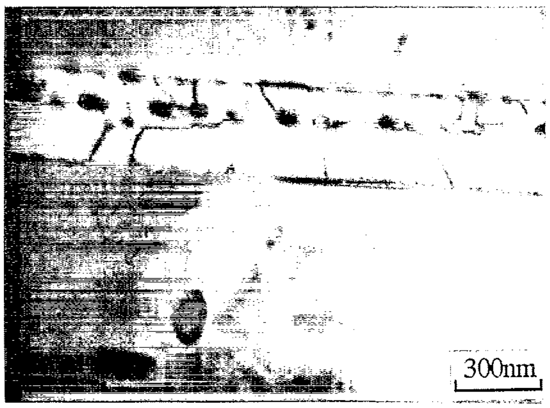

Fig. 5. TEM image of 0.65 Si alloy after creep under 200 MPa at 800 °C for 1213 h showing precipitates in the γ phase.

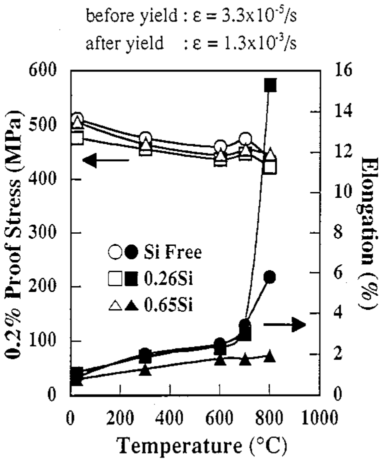

Fig. 6. Tensile properties of as aged alloys.

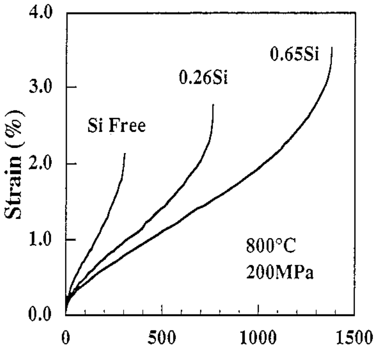

Fig. 7. Creep curves of alloys under 200 MPa at 800 °C in air.

The minimum creep rate of the 0.65 Si alloy was about one tenth of that of the Si-free alloy.

Assuming the creep of alloys to obey the power law, the minimum creep rates were analyzed according to the following conventional constitutional equation:

$$\dot{\varepsilon} = A\sigma^n \exp(-Q/RT)$$

where A is a constant, n is the stress exponent and Q is the apparent activation energy.

The stress dependence of the minimum creep rate is shown in Fig. 8 for 800 °C tests. The stress exponent was 6.4 for the Si-free alloy, which is large but still within the range 4.5–7.8 previously reported for single-phase and two-phase alloys [17–20]. The exponents for Si-containing alloys were larger, 8.0 for 0.26 Si and 10.3 for 0.65 Si, as for γ' precipitation strengthened Ni-base or oxide dispersion strengthened superalloys [21,22]. This proves that the precipitates of titanium silicide are effective in retarding creep deformation, especially under low stress.

The temperature dependence is shown in Fig. 9 for 300 MPa tests. The activation energy was 338 kJ mol^{-1} for the Si-free alloy, which is fairly close to the value previously reported for self diffusion in Ti–53Al [23]. The activation energies for Si-containing alloys were higher, 388–389 kJ mol^{-1}, but still within the range 300–560 kJ mol^{-1} previously reported for single-phase and two-phase alloys [17–20]. Generally, higher values have been obtained for dispersion strengthened alloys than for dispersoid-free alloys. Therefore the higher energies for Si-containing alloys indicate that the precipitates of titanium silicide enhance the creep resistance, especially at lower temperatures.

The specific creep strength of the alloys was compared with that of a conventional Ni-base cast superalloy Inconel 713C at 800 °C, Fig. 10. The strength of TiAl alloys dropped with time more rapidly than that of Inconel 713C and the strength of the Si-free alloy dropped below that of Inconel 713C. However, the Si-containing alloys showed better performance than Inconel 713C up to 10 000 h. The higher specific creep strength is encouraging for the replacement of conventional Ni-base superalloys by silicide precipitation strengthened TiAl.

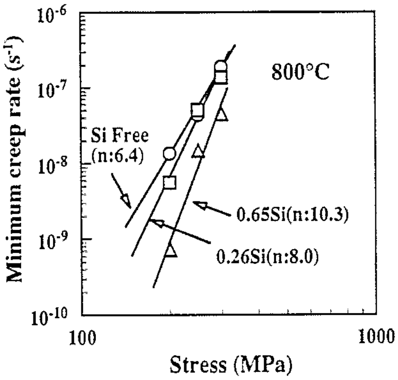

Fig. 8. Stress dependence of the minimum creep rate of alloys at 800 °C.

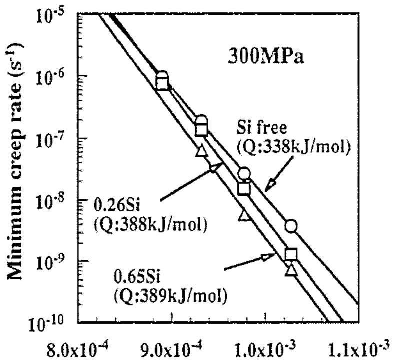

Fig. 9. Temperature dependence of the minimum creep rate of alloys under 300 MPa.

4. Conclusions

The microstructures and mechanical properties were surveyed of fully lamellar Ti–48Al–1.5Cr cast alloys containing up to 0.65 mol% Si. The results are as follows.

(1) In Si-containing alloys, a titanium silicide Ti_5Si_3 nucleates at γ–α_2 boundaries and grows in α_2 as fine precipitates less than 200 nm in size during aging at 900 °C for 5 h.

(2) The precipitation of Ti_5Si_3 does not degrade the tensile properties substantially from RT to 800 °C.

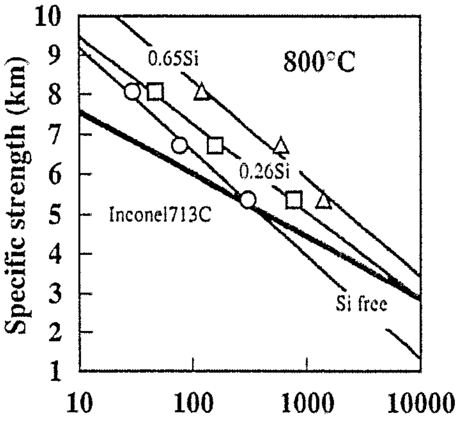

Fig. 10. Relation between the specific creep strength and creep rupture life of the Si-containing alloys and Inconel 713C.

(3) The precipitates retard the slow dislocation motion at elevated temperatures and enhance the creep resistance up to 850 °C with gains in stress exponent and activation energy from dispersion strengthening.

(4) The specific creep strength of Si-containing alloys is superior to that of conventional Ni-base cast superalloy Inconel 713C at 800 °C for 10 000 h.

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