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Internal Friction in Nickel-Base Superalloys in the kHz-Range at Temperatures between 20 °C and 1250 °C

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ABSTRACT. Damping measurements were carried out on two-phase (γ -matrix, γ' -precipitates) nickel-base alloys containing different volume fractions of γ' in order to achieve a better understanding of the strong elastic modulus decrease between 1000°C and 1100°C. For the investigation of the damping a free-free beam flexural vibration technique was applied. Nickel-base alloys with a high volume fraction of γ' , like CMSX-4, and the intermetallic phase Ni_3Al , the near γ' -phase, show two different damping peaks between 1000°C and 1200 °C. The measurements on alloys with a low volume fraction of the γ' -phase and of a near- γ matrix material lead to only one damping maximum in this high-temperature range. A comparison of the evaluated damping parameters leads to the assumption that the diffusion of nickel and aluminium atoms in the γ' -phase most probably is responsible for the relaxation processes in nickel-base alloys such as CMSX-4.

1. INTRODUCTION

Modern two-phase nickel-base superalloys with γ -matrix and γ' -precipitates, containing up to 70 vol.% of the ordered intermetallic precipitation γ' -phase $\text{Ni}_3(\text{Al,Ti})$, are often used in hot sections of stationary gas turbines and aircraft turbines, because of their excellent high-temperature properties. For the design of statically and cyclically loaded turbine components, knowledge of the elastic constants and their variation with temperature is a fundamental requirement.

In the high temperature range from 900°C to 1200°C the dynamic elastic moduli of these alloys show a strong decrease connected with an increase of the damping. In order to achieve a fundamental understanding of these phenomena damping measurements were carried out on several nickel-base alloys, containing different volume fractions of the γ' -precipitation phase, on specimens of a near- γ matrix alloy and on the intermetallic phase Ni_3Al , the near γ' -phase.

2. EXPERIMENTALS AND RESULTS

2.1 Materials and experimental methods

In this work results about two monocrystalline nickel-base alloys are presented, about CMSX-4 and Ni-Mo-Al-alloy R4. CMSX-4 is a two-phase material containing the L_{12} -ordered intermetallic γ' -phase $\text{Ni}_3(\text{Al,Ti})$ with a volume fraction of nearly 70% and the γ -matrix, a nickel-based solution. The alloy R4 is a Ni-Mo-Al-model material with a γ' volume fraction of less than 5%. The alloy compositions are given in Table 1. Further measurements were carried out on polycrystalline precipitation-free near- γ matrix mate-

rial and on L1₂-ordered Ni₃Al single crystals, the near γ' -phase. The composition of the matrix material is also given in Table 1.

The damping was measured in a free-free beam technique, by the flexural resonant vibrations of long thin rods (40 - 50 mm in length, 4 - 6 mm in diameter). A more detailed description is given in [1]. The measurements were carried out at temperatures between 20°C and 1250°C in the kHz frequency range (4 - 50 kHz), which partial overlap with the natural frequencies of turbine blades (2 - 8 kHz) [2].

Table 1: Compositions of the investigated alloys in weight %.

element	Ni	Al	Ti	Cr	Re	W	Mo	Co	Ta
CMSX-4	61.1	5.7	1.0	6.4	2.9	6.3	0.6	9.5	6.5
Ni-Mo-Al(R4)	79.0	7.0	-	-	-	-	14.0	-	-
matrix	52.7	-	-	15.8	5.0	8.0	1.8	16.7	-

2.2 Experimental Results

Several specimens of the mentioned materials were investigated. Each sample showed nearly no change in the damping and no significant and reproducible damping peak between 20°C and 900°C. Between 1000°C and 1200°C a strong increase in damping and a maximum are detected.

Figure 1: High-temperature damping: a) nickel-base alloy CMSX-4 b) Ni-Mo-Al-alloy R4.

More exact investigations of the high-temperature damping of CMSX-4 reveal two different damping peaks separated by about 70 K, for each mode of the flexural vibrations. The results are given in Fig. 1a, where the normalised damping $Q^{-1}/Q^{-1}(20^\circ\text{C})$ is plotted versus the temperature. The relaxation strength Δ according to Zener [3] has a value of nearly 0.2. In contrast to the behaviour of CMSX-4, the damping spectrum of the Ni-Mo-Al-alloy R4 shows only one maximum at high temperatures (Fig. 1b) and a relaxation strength of about $5 \cdot 10^{-2}$. In addition in Fig. 1b the γ' -solvus temperature is marked by a dotted vertical line at 970°C. The damping spectrum of the near- γ' material Ni₃Al is very similar to that observed for the alloy CMSX-4 with two relaxation peaks in the same temperature and resonant frequency range as shown in Fig. 2a. The relaxation strength Δ is 0.2. The measurements of the precipitation-free near- γ matrix material show only one maximum in the spectrum at high temperatures (Fig. 2b) and a strong exponential increase in damping up to very high temperatures, which is most probably due to grain boundary effects. In contrast to the results for CMSX-4 and Ni₃Al no significant decrease of the Young's modulus was observed. The relaxation strength is found to be nearly $2 \cdot 10^{-2}$.

Figure 2: High-temperature damping: a) Ni_3Al b) near γ -matrix material.

2.3 Relaxation Parameters

The presented results indicate that the observed damping is thermally activated. In this case the limit relaxation time τ_∞ and the activation energy ΔH are connected via $\tau = \tau_\infty \exp(\Delta H/kT)$, where τ is the relaxation time, k Boltzmann's constant, and T the absolute temperature.

Therefore relaxation parameters ΔH and τ_∞ can be determined by Arrhenius plots of the natural logarithm of the frequency at the damping maximum versus the reciprocal absolute temperature. The evaluated damping parameters of peak 1 and peak 2 of the nickel-base superalloy CMSX-4 and of Ni_3Al are given in Table 2, as well as the data of the damping maximum of the near matrix alloy. Unfortunately, the present results of the Ni-Mo-Al-alloy do not allow the evaluation of the relaxation parameters.

Table 2: Relaxation parameters.

alloy	Peak 1		Peak 2	
	ΔH [eV]	τ_∞ [s]	ΔH [eV]	τ_∞ [s]
CMSX-4	3.08	10^{-16}	2.67	10^{-13}
Ni_3Al	3.1	$5 \cdot 10^{-16}$	2.7	10^{-13}

matrix	ΔH [eV]	τ_∞ [s]
	2.83	10^{-13}

3. DISCUSSION

A comparison of the measured damping spectra and of the evaluated damping parameters show a good agreement between CMSX-4 and Ni_3Al . There is also a good agreement in the damping spectra of alloy R4 and the near matrix material. This indicates that most probably the relaxation processes in the γ' -phase are responsible for the observed damping in the nickel-base alloy CMSX-4. The high temperature exponential increase in damping of the polycrystalline near- γ matrix seems to be due to grain boundaries, because the monocrystalline Ni-Mo-Al-alloy does not show this effect.

The activation energies for nickel and aluminium diffusion in Ni_3Al , obtained in diffusion experiments by Frank et al. [4,5] on Ni_3Al single crystals are close to the data determined in this study for CMSX-4 and Ni_3Al . The investigations of Frank et al. also proved that the diffusion in Ni_3Al is due to thermal vacancies, not due to structural vacancies. Furthermore Badura et al. [6] found a strong formation of thermal vacancies in Ni_3Al between 950°C and 1250°C. In addition the difference in the activation energies for peak 1 and peak 2 for CMSX-4 and Ni_3Al , and of the nickel and aluminium diffusion in Ni_3Al amounts to 0.4 eV. This value of energy seems to be in the range necessary for the formation of an antisite defect in Ni_3Al [4,5,7].

In agreement with the results in [4,5] we propose the following diffusion mechanisms in the γ' -phase. Peak 2 is due to the nickel-diffusion in the nickel sublattice and peak 1 is caused by diffusion of aluminium via nearest-neighbour jumps on Al- or Ni-sites creating antisite defect atoms. Therefore the second diffusion mechanism needs a somewhat higher activation energy.

For getting further supporting arguments of the proposed diffusion mechanisms the aluminium and nickel atom jump rate Γ_i was calculated taking into account different jump distances, obtained from the lattice constant of γ' and the different numbers of nearest neighbours. The calculated atomic jump frequencies for aluminium and nickel correspond very well to the exciting frequencies for the different vibration modes for both damping peaks in CMSX-4. This indicates that the proposed diffusion mechanisms in Ni_3Al , the near γ' -phase, are also responsible for the damping in the alloy CMSX-4, which contains about 70 vol.% γ' -phase.

The damping maximum in the near-matrix material and in the alloy R4 is probably due to other diffusion effects. However, the present results do not allow exact conclusions about a specific diffusion mechanism.

4. CONCLUSIONS

The observed high-temperature damping of the nickel-base superalloy CMSX-4 is very similar to that of the near- γ' alloy Ni_3Al , while alloys with a low volume fraction of γ' and precipitation-free alloys show a different behaviour. This leads to the conclusion that the damping in nickel-base alloys with high γ' volume fractions is mainly determined by the damping mechanisms of the γ' -phase. The relaxation mechanisms proposed are the diffusion of aluminium and nickel in the γ' -precipitation phase: Peak 1 is caused by the diffusion of aluminium via nearest-neighbour jumps on Al- or Ni-sites which creates antisite defects, and peak 2 is attributed to the nickel diffusion in the nickel sublattice of the precipitation phase.

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