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FATIGUE CRACK GROWTH AT HIGH TEMPERATURE IN THE PM NICKEL BASE SUPERALLOY UDIMET 720 LI

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ABSTRACT

The paper presents preliminary results obtained at 725°C, and some comparisons with the data generated at 650°C. The tests were carried out at R=0.1 and with several frequencies and wave shapes, in order to study the effect of fiequency and dwell time on the FCGR. The appropriate dddt and da/dN; ΔK plots were obtained, and both the macro and the micromechanisms of failure were studied, using metallographic and SEM observations.

Some peculiarities were detected in the crack initiation and propagation behaviour of this material, specially at 725°C, such as non-uniform crack fronts and crack deviation from the main fracture plane in mode I conditions. Results of a preliminary analysis of these phenomena are presented, in an attempt to define more accurate and appropriate parameters and mechanisms to correlate the fatigue and creep crack growth. It is possible that both the processing conditions and the residual stress pattern could be the main factors for this crack propagation behaviour.

INTRODUCTION

The nickel base superalloys are still the most commonly applied materials for turbine discs in gas turbines used for aircraft and ship propulsion, and also in some types of industrial gas turbines for the production of electrical power. In these applications, the creep fatigue behaviour of the alloy is crucial for the selection of the parameters in service, like stress, rotational speed, temperature and surface resistance to erosion and hot corrosion.

For turbine discs, which is the main application covered in this work, conventionally cast and powder metallurgy alloys are used (1, 2).

Powder disc superalloys have higher static strength than conventional disc materials, and are, today, the most advanced nickel-base superalloys used in turbine discs (3,4). The new generation of PM alloys, such as Udimet 720 Li (4, 5), can give satisfactory performances, thus allowing an increase of stresses and temperatures. In PM superalloys, for example, it is possible to work with temperatures in the region of 700°C, without a significant loss of creep strength.

Udimet 720 Li is characteristic of the more recent very high strength PM alloys (3, 6). Typical heat treatment involves a solution treatment, followed by an oil quench and 2 ageing treatments. The oil quench, after the solution treatment, is necessary to meet tensile strength requirements for engine overspeed regulations. The quench prevents large γ' precipitates forming during initial cooling, and the subsequent duplex ageing achieves a uniform dispersion of intermediate sized y', with a very fine γ'' (2).

A detailed study was carried out on the fatigue crack growth behaviour of this alloy at 650°C (5, 6), which is apparently different from the one studied in other CC superalloys like IN71**8** and Waspalloy (7, **8).**

In (9), a review is given on the frequency transition behaviour of these materials, emphasising the role also played by the microstructure (grain size, precipitates, etc.).

The present paper gives fatigue and creep crack growth data obtained in CT specimens of PM Udimet 720 Li alloy, tested at 650 and, mainly, at 725°C. Results are also presented of the failure mechanisms observed with the SEM. The main objective of the study is to assess the influence of temperature and frequency on CGR.

EXPERIMENTAL DETAILS

The PM nickel base superalloy Udimet 720 Li is a fine grain material with an average grain size of 7μm, resulting from the manufacturing process of HIP, followed by extrusion of the powder. The microstructure shows an approximate percentage of **18%** of the γ' phase, with a small quantity of carbo-nitride inclusions. The heat treatment consisted on a 4 hours *soak* at 1080-1100°C, followed by oil quench up to 650°C during 24 hours and subsequent air cooling up to room temperature. Finally, an ageing treatment of 16 hours at 650°C was applied, followed by air cooling up to room temperature. The chemical composition and the mechanical properties of the material are given in Table 1 a) and b).

TABLE 1

A) **CHEMICAL COMPOSITION** OF THE **PM NICKEL BASE SUPERALLOY UDIMET** 720 **L1**

B) **MECHANICAL PROPERTIES (TENSILE TESTS)**

A)

Ni	Cr	Mo	Ti	Al	Co	Zr	W	Fe	B	C
59.3	16.2	3.2	5.1	2.6	14.5	0.035	1.7	0.072	0.022	<0.1

B)

Temperature (°C)	$\sigma_{0.2}$ (MPa)	σ_{UTS} (MPa)
20	1210	1640
200	1160	1590
400	1200	1560
500	1150	1550
600	1120	1490
700	1050	1250

$\sigma_{0.2}$ – Proof stress at 0.2% strain. σ_{UTS} –Ultimate tensile stress.

The fatigue and creep crack growth tests were carried out in a servohydraulic test machine with maximum load capacity of $\pm$ 100kN. CT specimens of the ASTM type were used, and these were machined from a service turbine disc. The specimen dimensions were standard 13 x 26mm (Thickness B x Width). *An* initial notch, obtained by friction cutting, was provided in each specimen with a crack depth, $a_o \cong 6.5$mm, giving an initial a/w ratio of 0.25.

The fatigue cycles were sinusoidal, with stress ratio, R=0.1 and frequencies of 0.25 and 5Hz. **A** test series was carried out with a trapezoidal load wave also with 0.25Hz frequency, but with 1 sec. ramp loading, l sec. ramp unloading, 1 sec. at maximum loading and 1 sec. at zero load. The creep tests were performed at the same maximum loads of the fatigue tests. Crack growth was monitored with a pulsed DC potential drop system, directly linked to the software of the testing machine. Calibration curves, crack area and crack length against the voltage drop were obtained by crack marking in the fracture surfaces of the specimens, after the tests. Linear relationships were obtained for the calibration.

Pre-cracking from the notch tip was carried out at room temperature, prior to the high temperature tests , and the crack was allowed to grow 1-1.5mm fiom the root of the notch, *so* that its tip could be outride the plastic zone around the notch.

Fracture surfaces of selected specimens were observed with the SEM to compare the cracking mechanisms for the different frequencies and temperatures. **A** conventional metallographic analysis of the crack propagation process is in progress.

RESULTS AND DISCUSSION

Crack propagation relationships, da/dN against the range of the stress intensity factor, AK, were obtained using appropriate curve fitting techniques to the raw crack length, a, and number of cycles, N, data obtained for each specimen. The individual values of C and m of the Paris law relationship are given in Table 2. Indicated also are the global obtained values of C and m, combining together all the da/dN; AK data for a specific test condition (temperature and frequency). In Table 2, r^2 are the values of the correlation coefficient of the linear regression of the results, and ΔK_0 is an approach to the threshold stress intensity factor obtained by extrapolation of the da/dN; AK correlation to a very low value of da/dN= 10^{-7}mm/cycle.

Plastic zone size values, r_p, for plane stress and plane strain conditions were calculated, using the LEFM relation, $r_p=\alpha(\Delta K/\sigma_{0.2})^2$, with $\alpha=1/6\pi$ for plane strain and $1/2\pi$ for plane stress. These r_p results are presented in Table 3 for AK values of 30 and 60 MPam$^{1/2}$. The values of $\sigma_{0.2}$ were obtained by curve fitting the tensile data given in Table 1b).

TABLE 2

VALUES OF C, m AND EXTRAPOLATED ΔK_0 OF PARIS LAW. R=0.1.
PM NICKEL BASE SUPERALLOY UDIMET 720 LI.

Ref.	T (°C)	f (Hz)	C (mm/cycle)	m	ΔK_0 (MPam$^{1/2}$)	r^2
1901	20	10	2.17x10^{-13}	4.0	8.24	0.86
1899/1	650	5	-----	----	----	----
1899/3	650	5	-----	----	----	----
1888/2	650	5	-----	----	----	----
Global	**650**	**5**	1.77x10^{-10}	2.32	2.11	0.973
1893/1	725	5	1.21x10^{-10}	2.67	2.20	0.956
1899/2	650	0.25	----	----	----	----
1888/1	650	0.25	----	----	----	----
1888/3	650	0.25	----	----	----	----
1891/1	650	0.25	----	----	----	----
Global	**650**	**0.25**	1.65x10^{-11}	3.35	3.40	0.891
189411	**650**	**0.25 T**	1.93x10^{-12}	4.15	4.51	0.83
189312	**725**	**0.25 T**	2.79x10^{-10}	3.29	1.47	0.966

TABLE 3

VALUES OF THE PLASTIC ZONE SIZE, r_p. R=0.1. PM NICKELBASE SUPERALLOY **UDIMET** 720 LI.

T (°C)	AK ($MPam^{1/2}$)	$r_{p\sigma}$ (mm)	$r_{p\varepsilon}$ (mm)
20	30	0.0978	0.0326
20	60	0.391	0.130
650	30	0.1235	0.0412
650	60	0.494	0.165
725	30	0.133	0.0444
725	60	0.532	0.178

$r_{p\sigma}$ - plane stress

$r_{p\varepsilon}$ - plane strain

It is expected that plane stress conditions will be predominant at the surface, while on the inside crack propagation will be mainly under plane strain.

Fig, 1 is a plot of the da/dN; ΔK data for 5Hz at room temperature, 650 and 725°C, together with the global correlations for C and m given in Table 2. The present data is compared with data available in the literature for a similar alloy (5, 6), and very good agreement was found.

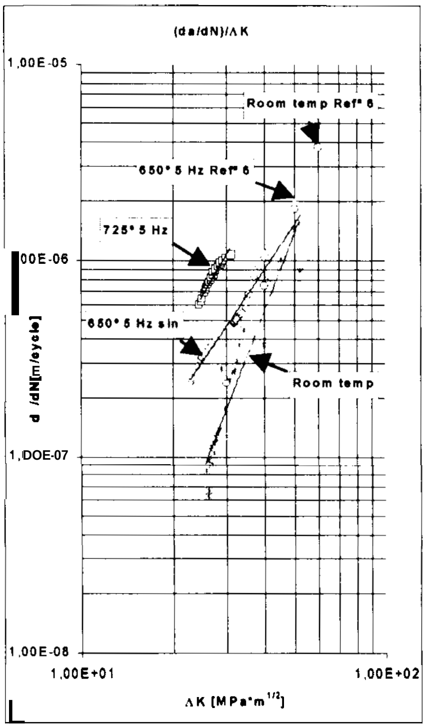

Fig. 1: da/dN vs. **AK.** CT specimens. R=0.1. f=5Hz. Room temperature, 650 and 725°C. PM nickel base superalloy Udimet 720 Li.

There is a slight increase in da/dN when the temperature is raised fiom 20 to 650°C. The increase in temperature from 650 to 725°C gives a three fold increase in crack growth rate, which is essentially due to the increase of the exponent m fiom 650 to 725°C.

For the fiequency of 0.25Hz (sinusoidal and trapezoidal), the results of da/dN; AK are shown in Fig. 2, both for 650 and 725°C. The change in load wave from sinusoidal to trapezoidal has only caused a minor increase in da/dN for the trapezoidal wave, which should be attributed to the fact that in the trapezoidal wave there is a small dwell time of 1 sec. at maximum load, inducing greater fatigue damage. In the sinusoidal wave the time interval close to the maximum load is smaller.

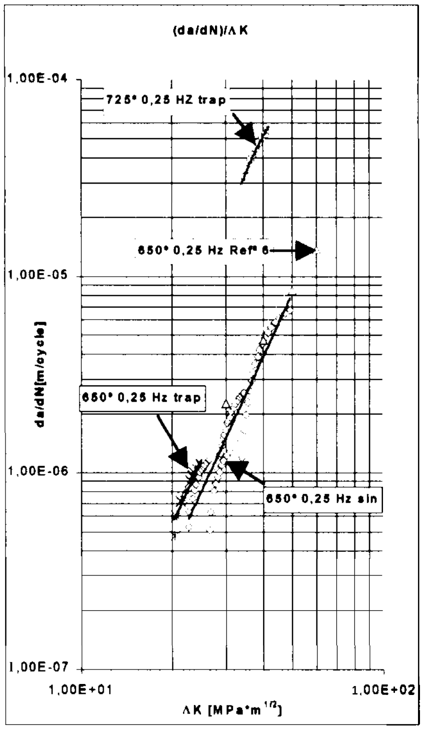

Fig. 2: da/dN **vs. AK.** CT specimens. R=0.1. f=0.25Hz, sinusoidal and trapezoidal. 650 and 725°C. PM nickel base superalloy Udimet 720 Li.

The trend of the results in Fig. 2 indicates that, for the frequency of 0.25Hz, the increase in temperature from 650 to 725°C gives a higher increase in crack speed than the frequency of 5Hz (Fig. 1). Thus, for the frequency of 0.25Hz there is an increase of near one order of magnitude in crack growth rate for the increase in temperature from 650 to 725°C.

The fracture surface transition form room temperature to 725°C is depicted in Fig. **3.** In the lower region (room temperature) the failure mode is mainly transgranular, and the striations are visible. For 725°C (upper region) the cracking mechanism is mixed, although predominantly intergranular with extensive grain boundary cracking. Some bands of striations are visible, induced by cyclic crack plasticity, which is greater than at room temperature, since the plastic zone size is also greater (RT at 725°C), significantly above the grain size of the material (Table **3).** At 725°C, intergranular cracking is favoured by increased oxidation and diffusion, providing an easier path for the propagation of the crack.

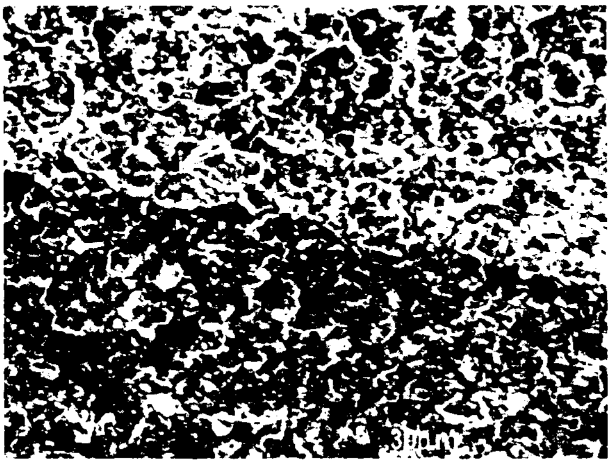

Fig. 3: Fracture surface in the transition from room temperature to 725°C. a=8 mm. f=0.25Hz trapezoidal. R=0.1. Magnification 1 K. PM nickel base superalloy Udimet 720 Li.

In the creep test, no incubation time type behaviour was observed, contrary to what was found in previous work published on IN718 (10). The crack propagated in a continuous manner, although with a curved shape inflecting towards the loading (mode I axis) under mixed mode I and II propagation, with mode II increasing with the crack length. Apparently, this cracking behaviour may occur in creep of nickel base superalloys, and has been briefly mentioned in the literature (11). Using a 3D scanner facility, the geometry and area of the curved crack was obtained and, fiom this, an equivalent crack length , a_{eq}, of a planar crack with the same area, A, as the curved crack and under mode I was obtained. Hence, $A=a_{eq}B$, where B is the specimen thickness.

For curved cracks under mode I loading, the stress intensity factors can be related by the equation (9)

$$K_{I\ell} = \cos^3 \frac{\theta}{2} K_{In} \qquad (1)$$

where the first member is the local component of K_I at the crack tip for the curved crack, with a tangent angle, 8, with the direction normal to the loading axis, and K_{In} is the nominal stress intensity factor for the straight crack with the same projected length, a. When θ=0 (straight crack under pure mode I), $K_{Il}=K_{In}$. Note that as θ decreases, K_{Il} increases and approaches K_{In}, i.e. the local K at the tip of a curved crack is below the nominal K for a straight crack with the same crack length under mode I crack propagation. Values of 8 were measured in the creep cracks, and these were found to vary between 0'' and 50°, approximately, as the rack length increased, and also the crack deflection.

For creep, both K_{Il} and K_{In} are the K values for the maximum static load in the specimen.

The plot dddt against K_{max} is shown in Fig. 4. The correlations obtained for K_{Il} and K_{In} were:

$$\frac{da_I}{dt} = 3.69x10^{-9} K_{,,}^{5.91} \qquad (2a)$$

$$\frac{da_I}{dt} = 4.79x10_{-6} K_{In}^{3.78} \qquad (2b)$$

where a_I is the projected length of the curved crack under mode I, i.e. $a_I=a_{eq}\cos\theta$.

It is seen that, for the same crack speed, K_{Il} is lower than K_{In}, and this variation is increasing as K_{In} is increasing, reflecting the increase of the angle θ as the crack grows. Additional work is in progress to analyse alternative parameters to correlate creep crack growth in curved cracks.

In Fig. 4 are also plotted the da/dN converted to dddt values of the plots in Figs. 1 and 2. The results show that, for the same K_{max} value, da/dt increases when the fiequency is decreasing, and the maximum value is reached in the creep loading.

The morphology of fatigue fracture surfaces obtained at 725°C can be analysed in Figs. 5 a), b). There is a very strong intergranular aspect, and the grain boundaries are defined in detail, specially at 0.25Hz since, for this fiequency, transgranular cracking zones are very limited. For 5Hz, some striation bands can be spotted in scattered grains, since the plastic zone sizes are significantly greater than the grain size. The fracture mode for this frequency can thus be classified as mixed, although the intergranular mode is predominant. Previous work carried out at 650°C has shown essentially a mixed failure mode, with similar contributions of intergranular and transgranular cracking (5, *6)*. At 725°C the intergranular trend is strongly dominant, specially at the lower fiequency of 0.25Hz, where the combined effects of oxidation and time are reflected by the extensive oxidation products and secondary cracking along the grain boundaries. Some minor void formations can also be detected at 0.25Hz, suggesting that some creep contributions can be expected.

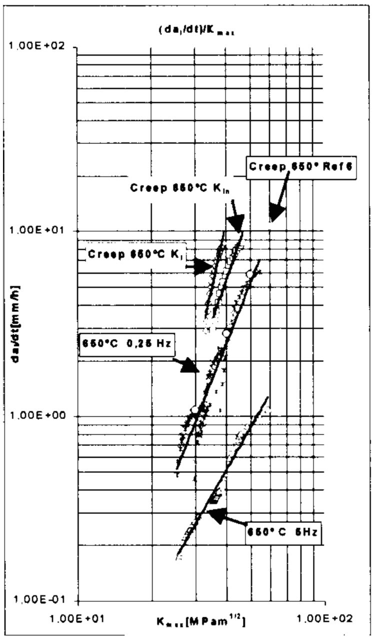

Fig. 4: dddt against K_{max} for creep and fatigue. 650°C. PM nickel base superalloy Udimet 720Li

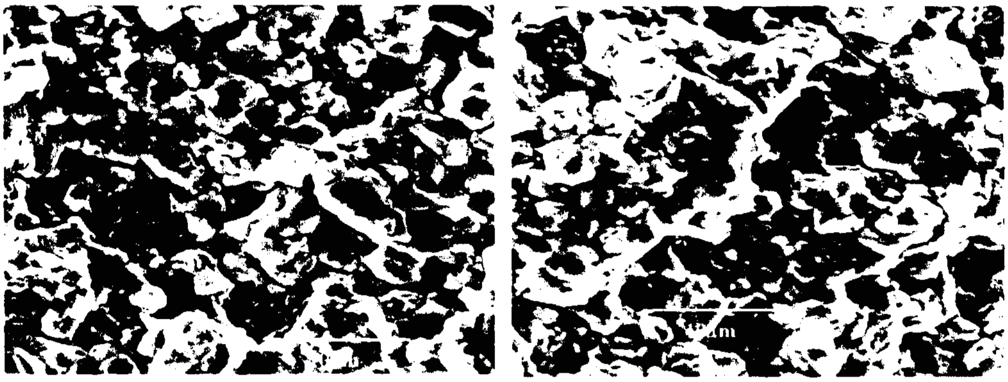

Fig. 5: SEM fracture surfaces of Udimet 720Li. a) 5Hz. b) 0.25Hz. .
Magnification **3K** PM nickel base superalloy Udimet 720Li. 725°C.

Fig. 6 depicts the fracture surface of a creep specimen tested at 650°C. The fracture mode is intergranular, with extensive void formation and coalescence. There are no signs of extensive oxidation products since, in this specimen, the testing time was reduced (short life creep), mainly due to the very high crack propagation speed. Grain boundary sliding is minor also, as a result of a combination of the small time involved in the test, high stresses and, probably, little creep ductility. The roughness of the fracture surface is higher than in the fatigue specimens (Fig. 5 and references **9,** 10)), due to the intergranular fracture mode with a fast crack propagation along the grain boundaries induced by microvoid coalescence. More work will continue on the creep study for higher temperatures and different levels of K. The use of the C* parameter will also be taken into account (10, 11).

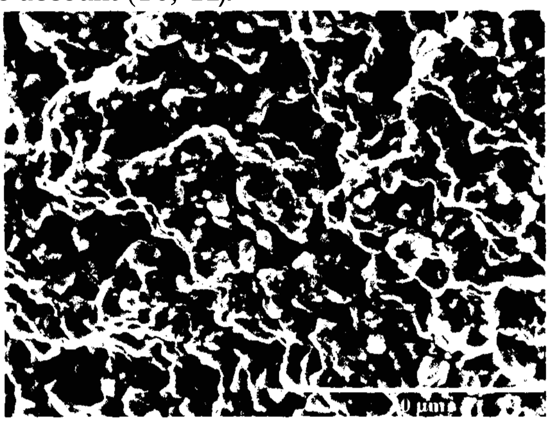

Fig. 6: SEM fracture surface of a creep specimen. PM nickel base superalloy Udimet 720Li. 650°C.
K=30 $Mpam^{1/2}$ Magnification 2K

CONCLUSIONS

- FCGR at 725°C is higher than at 650°C and at room temperature, both for the frequencies of 0.25 and 5Hz.
- The fiequency effect on the FCGR seems to be predominant over the temperature effect.
- At RT and 650°C, the main failure mode observed in FCG is mixed. At 725°C, the failure mode is essentially intergranular, specially at 0.25Hz.
- Curved cracking was obtained in creep with an increasing deflection of the crack fiom the mode I propagation, as the crack length and the range of the stress intensity factor increased. Crack speed was correlated with the local value of the stress intensity factor for the curved crack.
- Creep cracking at 650°C was intergranular, induced by microvoid coalescence, and CCGR was higher that the equivalent dddt values obtained in the fatigue loading at 5 and 0.25Hz.

REFERENCES

1. Meetham, G.W.(1982), *"Superalloys in Gas Turbine Engines", The Metallurgist and Materials Technologist,* pp. 187-192.
2. Harrison, G.F., Winstone, M.R., (1996) *"Aeroengine Applications of Advanced High Temperature Materials"* Proc. NATO ASI, Mechanical Behaviour of Materials at High Temperature, Eds. C. Moura Branco, R.O. Rotchie, V. Sklenijka, Kluwer Academic Press, The Netherlands, pp.109-126.
3. Eisen, W., (1996), *"PMSuperalloys – Past. Present and Future", Particulate Engineering, Materials in the World,* pp. 22-24.
4. Hattori, H. Takekawa, M., Furrer, D., Noel, R.J., (1996) *"Evaluation of P/M U720for Gas Turbine Engine Disc Application"* Proc, Superalloys'96, Eds. TMS, Pennsylvania, USA, pp. 705-712.
5. Tong, J. Byrne, J.(1998), *"Mechanism Map of U720Li Superalloy at 650°C"*, Proc. ECF12, 12" European Conference on Fracture,Pub. ESIS, Sheffield, UK.
6. Tong, J., Byrne, J., (1999) *"Effects of Frequency on Fatigue Crack Growth at Elevated Temperature", Fat. Fract. Eng. Mat. and Struct.,* 22, pp. 185-193.
7. Antunes, F.V., Branco, C.M., Ferreira, J.M., Byme, J., (March 2000), *"Stress Intensity Factor Solutions for Tunnelling Cracks under Mode I Loading"* to be published in *Fatigue and Fracture of Engineering Materials and Structures..*
8. Antunes, F.V., (1999), *''Influence of Frequency, Stress Ratio and Stress State on Fatigue Crack Growth in Nickel Base Superalloys at Elevated Temperature",* PhD Thesis, Dep. of Mechanical and Manufacturing Engineering, University of Portsmouth, UK.
9. Branco, C.M., Byrne, J., Hodkinson, V., (1996), *"Elevated Temperature Fatigue Crack Growth of Nickel Base Superalloys: a Review and Modelling, Parts I –II",* Proc. NATO/ASI, Mechanical Behaviour of Materials at High Temperature, Sesimbra, , Portugal, pub. by Kluwer, The Netherlands, pp. 93-135.
10. Branco, C.M., Baptista, J., Byrne, J., (1999), *"Crack Growth under Constant Sustained Load at Elevated Temperature in IN718 Superalloy", Materials at High Temperature,* 16, 1, pp. 27-35.
11. Webster, G., Ainsworth, R.A., (1994), *"High Temperature Component Life Assessment",* Chap. 6, Ed. Chapmann & Hall, UK.

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