EFFECT OF HIP ON LOW CYCLE FATIGUE OF MAR-M247 AT 900°C

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Abstract

Polycrystalline nickel-base superalloy MAR-M247 is used for high temperature applications requiring excellent combination of fatigue properties, creep resistance and surface stability. These superior high temperature characteristics derive from the microstructure which habitually consists of face centred cubic matrix γ and precipitate γ´ ($L1_2$ type ordered structure).

In the present work, the high temperature low cycle fatigue behaviour of cast nickel-base superalloy MAR-M247 in as received condition and in hot isostatically pressed (HIP) condition was studied. The microstructure of the materials is characterized by dendritic grains, carbides and casting defects. Distribution and size of defects in both materials were studied. Isothermal low cycle fatigue (LCF) tests were performed on cylindrical specimens under total strain control at 900°C in air. Cyclic stress-strain response and fatigue life of both materials were assessed. Beneficial effects of HIP process on cyclic stress-strain and fatigue life curves are discussed.

Keywords: MAR-M247, high temperature, low cycle fatigue

1. INTRODUCTION

Nickel base superalloys are class of materials exploited at high proportion of their actual melting point. They consist of many elements in a variety of combinations to achieve a desired result. They exhibits excellent combination of mechanical strength, creep resistance and surface stability, which is commonly used for high pressure stages of aircraft, marine, industrial and vehicular gas turbines [1, 2]. These superior high temperature properties derive from the microstructure which habitually consists of the face centred cubic matrix γ and precipitate γ´ ($L1_2$ type structure), carbides and exceptionally adverse topologically close packed (TCP) phases [3]. Disregarding type, all engines have moving parts which experience alternate loading during service. Generally, the low cycle fatigue tests (LCF), are designed to cause failure of the sample after a relatively small number of cycles owing to the large amount of plastic deformation. Under total strain control, cyclic behaviour of the material (hardening or softening) can be assessed by its stress response as a function of number of cycles [4, 5].

In this article, we report LCF behaviour of vacuum melt, nickel-base superalloy MAR-M247. It is primarily used for high temperature applications to integral wheels and turbine rotor blades and was developed in early 1970s at Martin Metals Corporation [6, 7]. The alloy has high volume fraction of gamma prime precipitates (over 60%) and high refractory element content. It demonstrates very good castability [8], excellent oxidation resistance and outstanding mechanical properties at elevated temperature [9]. Necessary heat treatment consists of solution annealing 1200 °C/2h and subsequent hardening annealing 870 °C/2h [8]. Internal defects significantly affect the scatter of low cycle fatigue and creep properties [10]. Moreover, these defects act as stress concentrators and facilitate the initiation of cracks and their subsequent propagation [11]. For these reasons it is extremely important to eliminate the amount of shrinkage and microporosity to a minimum. Hot isostatic pressing (HIP) is a manufacturing process used to reduce the porosity and thereby reducing the variance of mechanical properties [12, 13]. It is carried out before thermal treatment at temperature of 1200 °C/240min and pressure 100 MPa.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

The material studied was polycrystalline cast nickel-base superalloy MAR-M-247 supplied by PBS, Velká Bíteš, a.s in the form of conventionally cast (CC) rods. One half of the casting rods were hot isostatically pressed (HIP) and all rods were subsequently heat-treated. The material is typical of a coarse dendritic structure with carbides, eutectics and shrinkage pores whose maximum size was found to be 0.62 mm for the CC and 180 μm for the HIP version. **Table 1** shows the size of defects. Defects were measured on an area of 11.7 cm^2 and were approximated by an ellipse the main axis of which was used to determine the linear size of the defect. Fatigue specimens were machined parallel to the rod axis. **Fig. 1** shows the typical structure in section perpendicular to the rod axis with coarse polygonal grains in the middle and elongated grains around the edge of the specimen. An average grain size of polygonal grains, found using linear intercept method, was 2.1 ± 0.3 mm. Composition of MAR-M-247 superalloy used was obtained by chemical analysis and it is listed in **Table 2**.

Table 1 The linear size of casting defects

Size of defects		**< 20 [μm]**	**20 - 100 [μm]**	**0.1 - 0.5 [mm]**	**0.5 - 1 [mm]**
Number of defects	CC	36	45	8	2
	HIP	25	13	1	0

Fatigue experiments were carried out in computer controlled servo-hydraulic testing machine MTS 810 with a maximum load of ± 100 kN. The cylindrical test specimens have a gauge length and diameter of 15 and 6 mm, respectively. The gauge length was mechanically ground. The gauge length of some specimens was polished before testing to facilitate the surface relief observation.

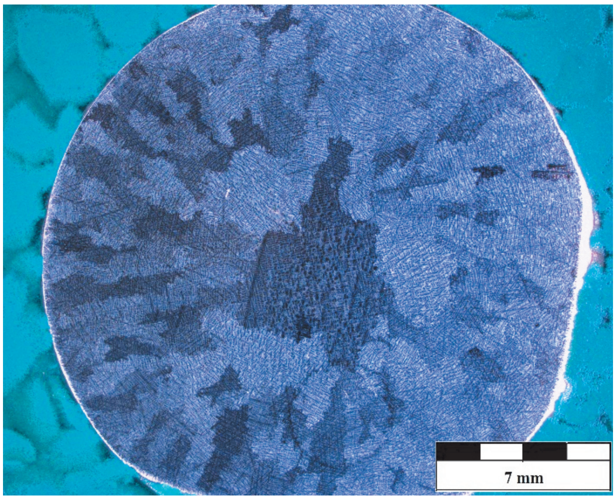

Fig. 1 Microstructure with polygonal and elongated grains (optical microscope)

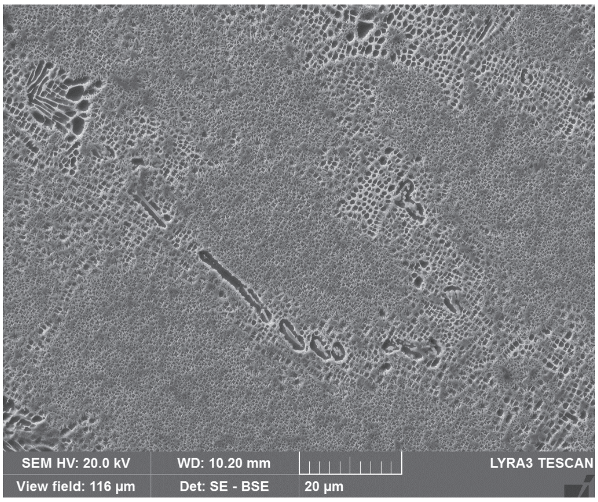

Fig. 2 The microstructure of MAR-M-247 after heat treatment (REM)

All LCF tests were performed in a push-pull cycle under total strain control conditions using a fully reversed triangular waveform (R_ε = -1) in air at a temperature of 900 °C. Specimens were heated in a resistance furnace with temperature gradients within ± 2 °C. Total strain rate of $2\cdot10^{-3}$ s^{-1} and total strain amplitude were kept constant in each test. The strain was measured and controlled with an extensometer. The cyclic stress-strain data were recorded and the hysteresis loops were obtained at some pre-selected number of cycles. Plastic strain amplitude obtained from the half of the hysteresis loop width and stress amplitude were acquired at half-life.

Table 2 The chemical composition of superalloy MAR-M247 [wt.%]

C	Cr	Co	Mo	W	Ta	Ti	Al	B	Zr	Hf	Ni
0.15	8.37	9.91	0.67	9.92	3.05	1.01	5.42	0.015	0.04	1.37	Bal.

3. RESULTS AND DISCUSSION

3.1 Microstructural observation

No difference was found in the microstructure between CC and HIP samples. The characteristic microstructure of alloy MAR-M247 after heat treatment is shown in **Fig. 2**. The arrangement and size of precipitates in dendritic arms differ from those in the interdendritic areas. Coarse precipitates are found in the interdendritic areas while fine precipitates are present in dendritic arms. Both coarse and fine precipitates are cuboidal. Besides very small spherical γ' precipitates were observed in a γ matrix (see **Fig. 3**). The spherical precipitates were not found in specimens after fatigue tests. Carbides are present particularly at grain boundaries and in interdendritic areas. No rafting was observed in fatigued specimens.

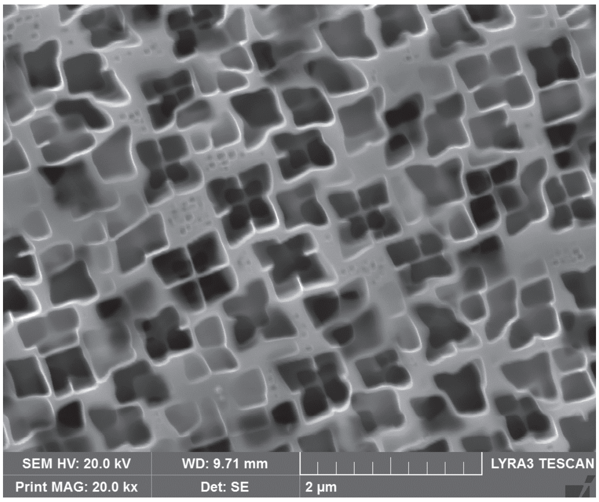

Fig. 3 Detail morphology of cuboidal and spherical precipitates within dendritic arms

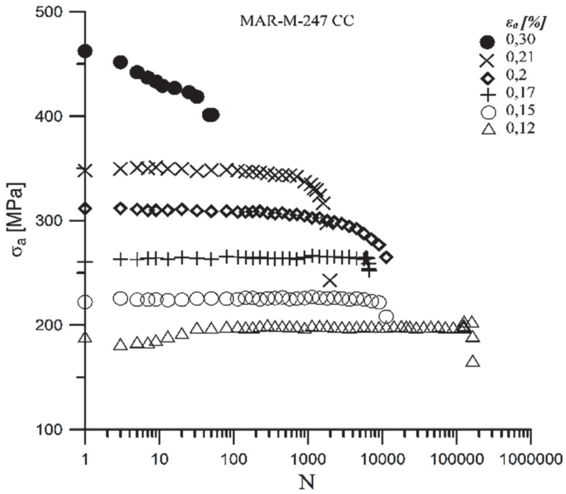

Fig. 4 Fatigue hardening/softening curves of MAR-M-247 CC

3.2 Stress response

The stress amplitude versus the number of cycles N acquired for CC and HIP specimens for various total strain amplitudes is shown in **Fig. 4** and **Fig. 5**. The hardening/softening curves vary with the stress amplitude. For both materials the saturated stress response is typical for medium and low amplitudes. High amplitude cycling results in cyclic softening.

An important result of LCF studies is the cyclic stress-strain response reflecting the steady state behaviour of the studied material under LCF conditions [4, 5, 14]. Cyclic stress-strain curve (CSSC) is determined as the dependence of the stress amplitude σ_a on plastic strain amplitude ε_{ap} in stabilised state at half-life (see **Fig. 6**). Experimental data were approximated by the power law:

$$\log \sigma_a = \log K' + n' \log \varepsilon_{ap} \quad (1)$$

and fatigue hardening coefficient K' and fatigue hardening exponent n' were evaluated using linear regression analysis. They are shown in **Table 3**.

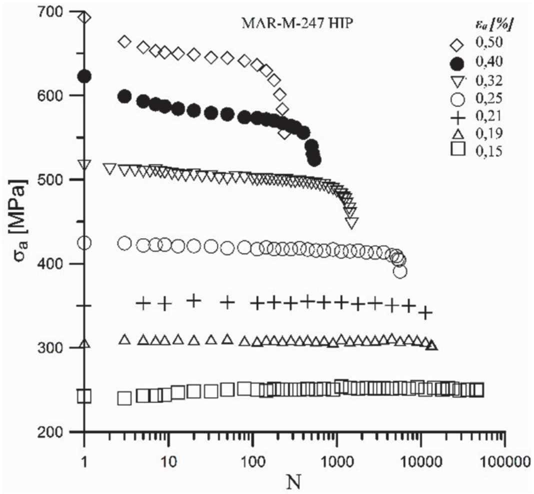

Fig. 5 Fatigue hardening/softening curves of MAR-M-247 HIP

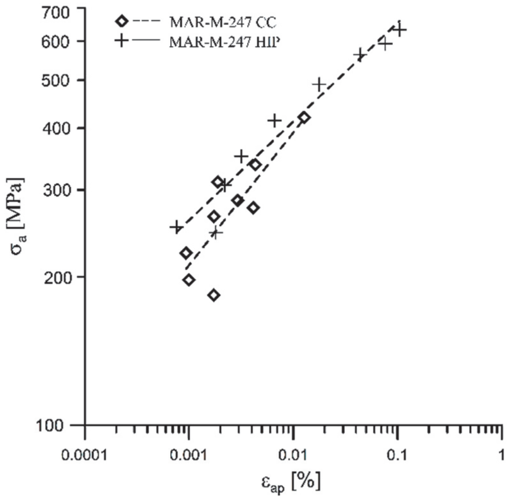

Fig. 6 CSSC of the CC and HIP MAR-M-247

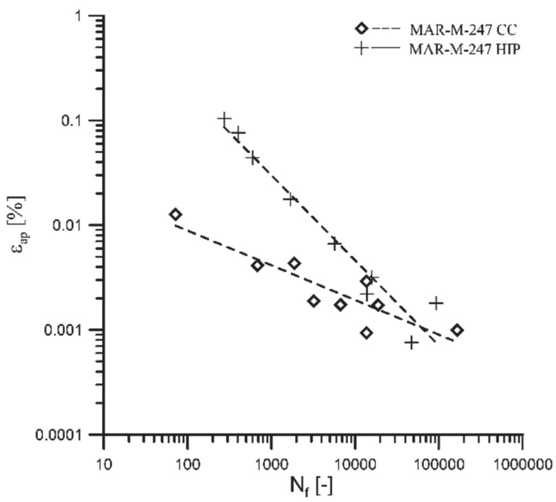

Fig. 7 Coffin-Manson fatigue life curves

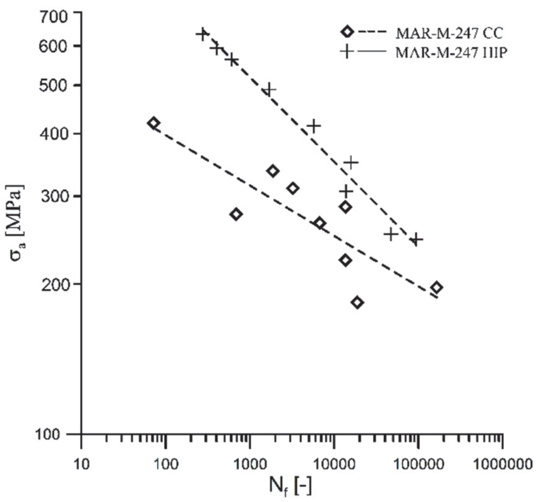

Fig. 8 Basquin fatigue life curves

Table 3 Parameters of CSSC, Basquin, and Coffin-Manson curves of conventionally cast and hot isostatically pressed MAR-M-247

	K' [MPa]	n'	σ'_f [MPa]	b	ε'_f	c
CC	4660	0.269	678	-0.101	0.0005	-0.33
HIP	2602	0.199	1882	-0.169	0.146	-0.81

3.3 Fatigue life

Figs. 7 and 8 show the curves of fatigue life of the CC a HIP MAR-M-247. The plastic strain amplitude ε_{ap} at half-life versus number of cycles to failure N_f is plotted in bilogarithmic representation (see **Fig. 7**). The Coffin-Manson law expressed in the form

$$\log 2N_f = 1/c\ (\log \varepsilon_{ap} - \log \varepsilon'_f) \qquad (2)$$

is applied to fit experimental data. Fatigue ductility coefficient ε'_f and fatigue ductility exponent were evaluated using non-linear regression analysis and are shown in **Table 3**. The results show that the fatigue life of the HIP specimens is significantly higher than that of CC specimens in the high amplitude domain. For low amplitudes, the fatigue life of both materials is very similar.

Fig. 8 shows fatigue life curves in the representation of the stress amplitude σ_a at half-life vs. number of cycles to failure N_f. Experimental data were fitted by the Basquin law:

$$\log 2N_f = 1/b\ (\log \sigma_a - \log \sigma'_f) \quad (3)$$

and material parameters b and σ'_f were determined and their values are shown in **Table 3**. It can be seen from **Fig. 8** that the Basquin curve of HIP material is shifted to higher fatigue life. The shift is more pronounced in the high amplitude domain.

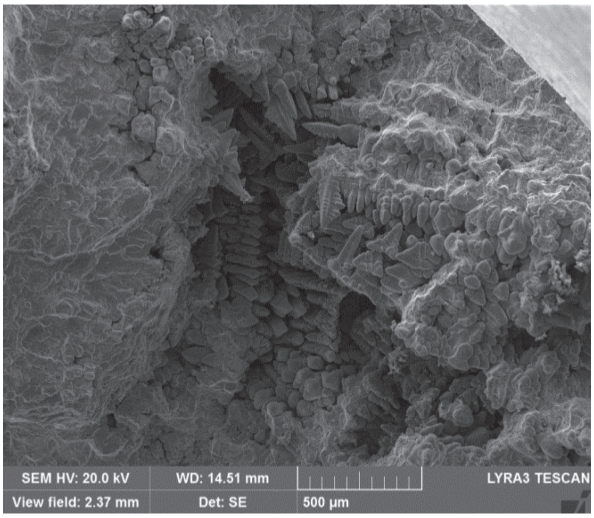

Fig. 9 Fatigue crack initiation site at the surface in vicinity of casting defect

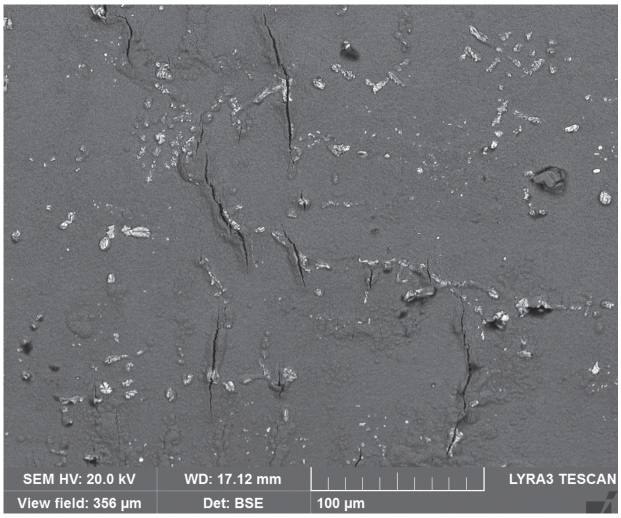

Fig. 10 Cracks initiating from carbide inclusions

Table 1 shows that the density and size of casting defects is higher in CC material. Therefore, both fatigue crack initiation and crack growth are accelerated in the CC material. It results in the fatigue life decrease of CC specimens compared to HIP superalloy [12] which was observed experimentally (see **Figs. 7** and **8**).

3.4 Fracture surface observation

Fractographic analysis of the fracture surfaces was performed in specimens with varying amplitude of the total strain. Regardless of loading amplitude, for conventionally cast specimens crack initiation was observed mostly at the surface in the vicinity of casting defects (see **Fig. 9**). Whereas for low amplitude domain of hot isostatically pressed samples cracks were also initiated from microshrinkage and created so-called fish eyes, but at high loading level some cracks were initiated from carbide inclusion, as seen in **Fig. 10**.

3.5 Conclusions

The following conclusions can be drawn from the study of LCF behaviour of CC and HIP specimens of MAR-M-247 superalloy:

- The size and density of casting defects of hot isostatically pressed specimens are considerably reduced in comparison with CC material.
- The microstructure of precipitates and carbides of both studied materials is similar. Only small changes in microstructure occur during high temperature LFC tests.
- Stress response at half-life of hot isostatically pressed material is similar to that of conventionally cast superalloy.

- Low cycle fatigue tests conducted on MAR-M-247 clearly show improvement in fatigue life for hot isostatically pressed specimens both in the Basquin and Coffin-Manson representation.
- Fatigue crack initiation mostly starts at the surface in the vicinity of casting defects or carbide inclusion.

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