EFFECT OF CASTING CONDITIONS AND HEAT TREATMENT ON HIGH TEMPERATURE LOW CYCLE FATIGUE PERFORMANCE OF NICKEL SUPERALLOY INCONEL 713LC

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Abstract

The present work is focused on the study of high temperature low cycle fatigue behaviour of Inconel 713LC produced by a vibratory investment casting (VIC) in as-cast conditions and in the condition after heat treatment (HT) consisting of hot isostatic pressing (HIP) followed by precipitation hardening. Low cycle fatigue tests were carried out on cylindrical specimens in symmetrical push-pull cycle under strain control with constant total strain amplitude and strain rate at 800 °C in air. Hardening/softening curves and fatigue life curves of both materials were assessed and compared with data of Inconel 713LC produced by a conventional investment casting (CIC). Cyclic hardening can be observed in the high amplitude domain while saturated stress response is apparent for low amplitude cycling for all material batches. Data presented in Basquin representation show an increase in fatigue life of both VIC batches compared to the CIC batch, however, no effect of HT on fatigue life of Inconel 713LC produced by VIC was observed. In contrast, the heat treated Inconel 713LC demonstrates slightly higher fatigue life in Coffin-Manson representation. The microstructure of both superalloys was studied by means of scanning electron microscopy (SEM). The microstructure of superalloy is characterized by dendritic grains with casting defects. It comprises the γ matrix, cubic γ´ precipitates, eutectics and carbides. The effect of the VIC and HT on fatigue performance and microstructure of Inconel 713LC is discussed.

Keywords: Inconel 713LC, vibratory investment casting, hot isostatic pressing, high temperature low cycle fatigue, stress-strain response

1. INTRODUCTION

Nickel-based superalloy Inconel 713LC is an extensively used cast material for a diverse scale of high temperature components mainly due to its very favourable cost and outstanding fatigue and creep performance [1,2]. It is produced by a conventional investment casting method and as such Inconel 713LC contains casting defects that can adversely affect lifetime [3]. Hot isostatic pressing (HIP) technique provides an effective tool to heal casting defects [4,5], though, it can negatively affect the morphology of the $L1_2$ ordered γ´ precipitates and to restore the microstructure additional heat treatment (HT) is crucial but making production more expensive. To reduce the costs and provide material with diminished size and amount of casting defects a modification of the conventional investment casting (CIC) could be done via including vibrations during solidification.

The present work is focused on the study of high temperature low cycle fatigue behaviour of Inconel 713LC produced by the vibratory investment casting (VIC) in as-cast conditions and in the condition after heat treatment (HT) consisting of hot isostatic pressing (HIP) followed by precipitation hardening. A comparison of data obtained from low cycle fatigue tests of Inconel 713LC produced by the VIC and of Inconel 713LC produced by the CIC obtained previously [6] is provided.

2. EXPERIMENT

A low carbon (LC) version of Inconel 713 was supplied by PBS, Velká Bíteš, a.s. in the form of button-end rod samples made by the CIC and VIC with a gauge length and diameter of 14 mm and 8 mm, respectively.

Selected samples produced by the VIC were heat treated. The HT process consists of HIP (1200 °C / 4 h / 100 MPa) followed by precipitation hardening (750 °C / 4h). The average grain size of the VIC batch and the CIC batch found using linear intercept method was 240 µm ± 47 µm and 2.3 mm ± 0.4, respectively. The chemical composition of Inconel 713LC in wt% is as follows: Ni-11.72Cr - 4.19Mo - 0.05C - 5.97Al - 0.69Ti - 1.95Nb - 0.03Ta - 0.1Zr - 0.007B. The superalloy is typical of a dendritic structure with shrinkage pores (**Figure 1**). The microstructure consists of γ matrix, γ´ strengthening phase, eutectics and carbides in a form of Chinese script. Cylindrical specimens with diameter and gauge length of 6 and 15 mm, respectively, were applied to perform high temperature low cycle fatigue tests. Fatigue tests were conducted in a fully reversed push-pull cycle ($R\varepsilon$ = -1) under strain control mode with constant strain rate 2 x 10^{-3} s^{-1} at 800 °C in air. Details of high temperature low cycle fatigue testing and tests evaluation could be found elsewhere [7]. Microstructural investigations were accomplished by means of the scanning electron microscope (SEM - TESCAN Lyra3 XMU) equipped with the energy dispersive X-ray (EDX) spectroscopy analyser.

3. RESULTS AND DISCUSSION

The initial microstructure of Inconel 713LC for all material conditions is shown in **Figure 1(a-c)** using backscatter electron imaging in channelling contrast. Vibrations support the nucleation of new grains during the solidification and thus effectively reduce the grain size. An introduction of vibrations in a casting process contributed to a reduction not only of the average grain size (compare **Figure 1a** and **Figure 1b**) but also the size of casting defects. The maximum size of shrinkage pores was 300 µm in diameter in case of the CIC batch and 90 µm for the VIC batches. Inlets in the right upper corner of **Figures 1 (a-c)** show the SEM image of γ´ precipitates shape and it can be noticed that application of the HT into the production chain implies a tendency of γ´ precipitates to form an array of cubes (**Figure 1c**). The mechanism of γ´ precipitates coarsening is generally controlled by the lattice misfit between the γ matrix and γ´ strengthening precipitates producing the elastic strain energy and interfacial energy in the material, allowing higher mobility of interface due to the higher density of interfacial dislocations [8-10]. This phenomenon in a conjunction with various heat treatment conditions has been intensively studied by Ricks [11] in a wide range of nickel-based superalloys and it was found that the coherency stresses related to the lattice misfit influence also the morphology of the γ´ precipitates, which is in a good agreement with observed morphology of γ´ precipitates of the HTed Inconel 713LC. Besides, the anisotropic relaxation of the coherency stresses induced by the motion of dislocations during fatigue or creep loading can bring about another morphological change of γ´ precipitates. **Figure 1d** shows incipient ‘‘rafting’’ of γ´ precipitates of a CIC sample fatigued at 800 °C with a total strain amplitude of 0.45 % [12-14]. Such a significant change in the shape of γ´ precipitates was found only in the CIC batch (compare with **Figure 1e** and inlet in **Figure 1f**) and, moreover, only in samples fatigued with the total strain amplitudes higher than 0.44 %. Cyclic straining with lower amplitudes does not affect the microstructure at all. This indicates the dependency of the rafting on the applied macroscopical stress as it was reported by Yu et al [15]. However, in the VIC batch, there is a tendency of γ´ precipitates to become more or less rounded (**Figure 1e**). The γ´ precipitates of the VIC + HT batch seems to be even more resistible to rafting (inlet in **Figure 1f**) than of the VIC or CIC batch. With a decrease in the grain size, the process of fatigue crack initiation at grain boundaries and subsequent propagation of fatigue cracks along grain boundaries (**Figure 1f**) begin to play more critical role [16], mainly due to a higher incidence of impurities at grain boundaries.

Figure 2 characterizes the stress response of Inconel 713LC during cyclic straining at 800 °C in the representation of the stress amplitude versus the number of elapsed cycles. The cyclic hardening/softening curves were obtained for various total strain amplitudes for all material batches. Regardless of the material batch, the character of the hardening/softening curves of Inconel 713LC depends on the strain amplitude. The high amplitude domain is characterized by fatigue hardening, while saturated stress response is found in the medium and low amplitude domain.

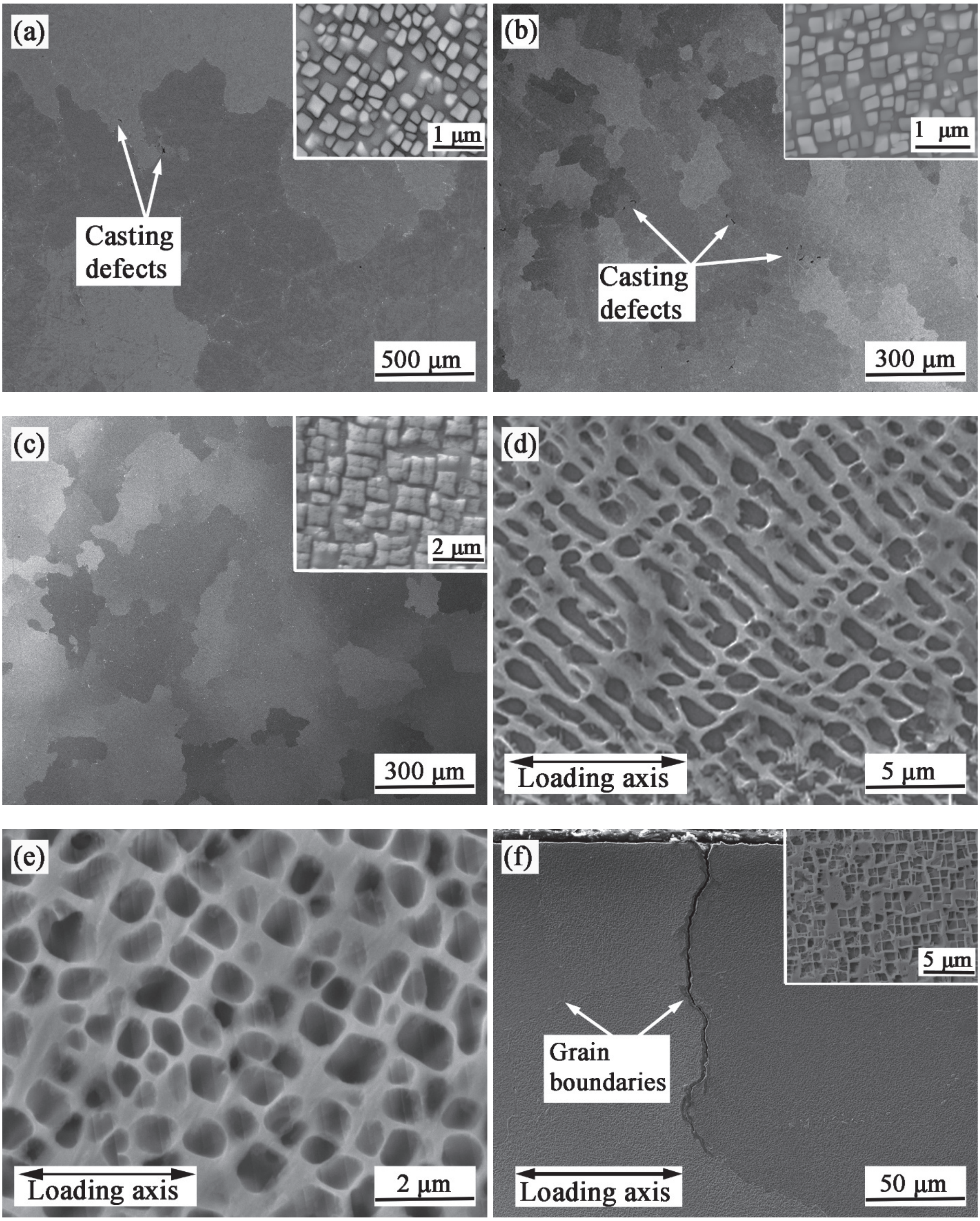

Figure 1 Microstructure of Inconel 713LC showing dendritic grains and morphology of γ´ precipitates produces via: (a) CIC conventional investment casting, (b) VIC vibratory investment casting, (c) VIC + HT vibratory investment casting with subsequent heat treatment, (d) precipitates morphology after fatigue (CIC sample), (e) precipitates morphology after fatigue (VIC + HT sample), (f) fatigue crack initiation and propagation along grain boundary (VIC sample)

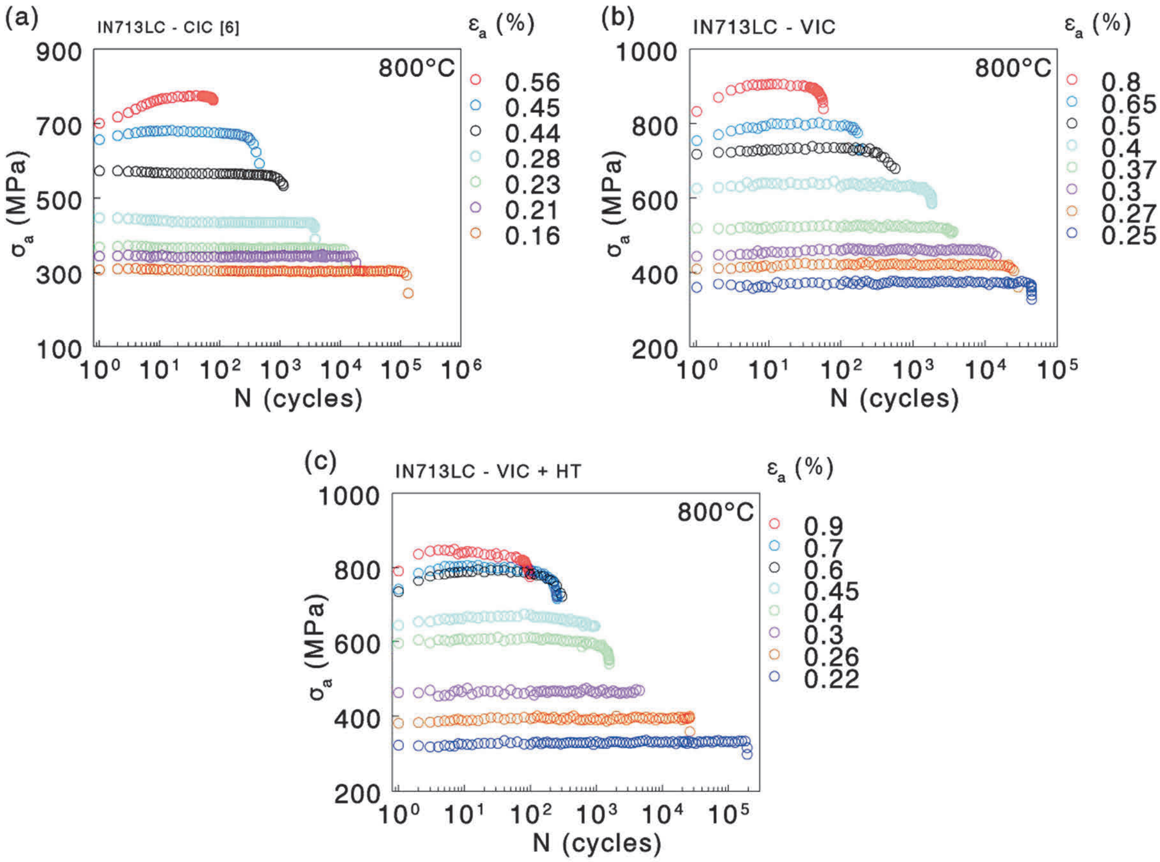

Figure 2 Cyclic hardening/softening curves of Inconel 713LC: (a) CIC, (b) VIC, (c) VIC + HT

Fatigue life curves in the representation of the stress amplitude σ_a versus the number of cycles to fracture N_f are plotted in **Figure 3a**. The Basquin law expressed in the form:

$$\log 2N_f = \left(\frac{1}{b}\right) \log \sigma_a - \left(\frac{1}{b}\right) \log \sigma_f^{\prime} \quad (1)$$

fits the experimental data obtained in low cycle fatigue tests. The fatigue strength coefficient $\sigma_f^{\prime}$ and the fatigue strength exponent *b* were evaluated by regression analysis using least squares fitting and their values are listed in **Table 1**. It can be seen from Figure 3a that the Basquin curves for the VIC and VIC + HT batches of Inconel 713LC are for the same fatigue life shifted of approximately 100 MPa to higher stress amplitudes in comparison with the CIC Inconel 713LC. The shift to higher fatigue lifetime of the VIC and VIC + HT batches can be attributed to the grain size effect [17]. **Figure 3a** shows that the fatigue life in the Basquin representation is almost the same for the VIC and VIC + HT batch in the whole range of the stress amplitudes.

The plastic strain amplitude ε_{ap} vs. N_f is plotted in a bilogarithmic representation in **Figure 3b**. The values of ε_{ap} were established as the half width of the hysteresis loop at half-life. Experimental data were approximated by the Coffin-Manson law:

$$\log 2\mathrm{N_f} = \left(\frac{1}{c}\right) \log \varepsilon_{\mathrm{ap}} - \left(\frac{1}{c}\right) \log \varepsilon_{\mathrm{f}}^{\prime} \quad (2)$$

where $\varepsilon_f^{\prime}$ is the fatigue ductility coefficient and *c* is the fatigue ductility exponent. The parameters were evaluated by regression analysis and are listed in **Table 1**. Data presented in **Figure 3b** show a positive impact of the VIC on fatigue life in the whole range of tested amplitudes. An additional improvement achieved by the introduction of the HT can be found in the high amplitude domain of the Coffin-Manson diagram. This behaviour can arise from a higher stability of arrays of γ´ cubes in the VIC batch after HT in comparison with individual γ´ cubes in the VIC batch (see again **Figure 1**), where the cyclic straining at 800 °C in high amplitude domain resulted in a tendency of γ´ precipitates to begin to round (VIC sample - **Figure 1e**).

Table 1 The parameters of Basquin and Coffin-Manson fatigue life curves of Inconel 713LC

Material batch	σ_f' (MPa)	*b*	ε_f' (-)	*c*
CIC	2080	-0.16	0.098	-0.81
VIC	1790	-0.14	0.465	-0.91
VIC + HT [6]	1740	-0.15	0.039	0.78

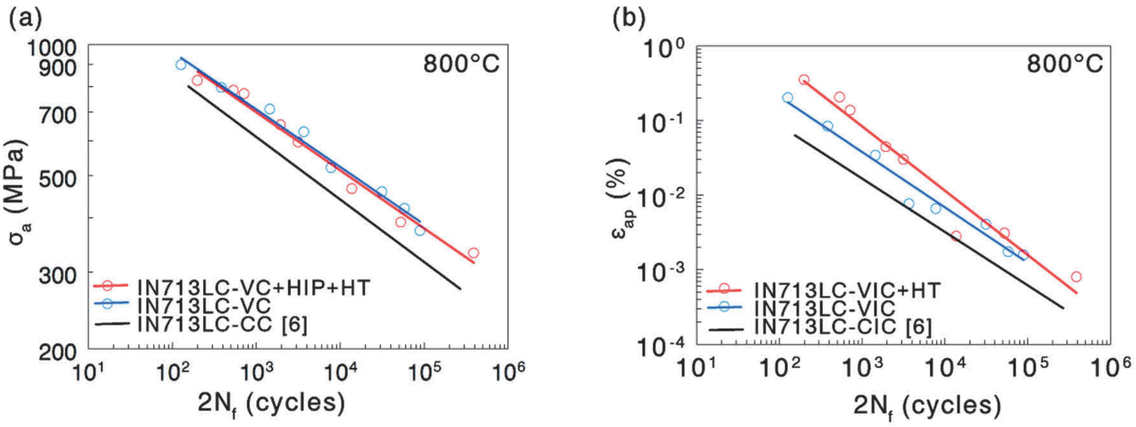

Figure 3 Fatigue life curves: (a) Basquin representation, (b) Coffin-Manson representation

4. CONCLUSIONS

The following conclusions can be drawn from the study of high temperature low cycle fatigue behaviour of Inconel 713LC produced by conventional investment casting and vibratory investment casting.

a) The average grain size and maximal size of casting defects of material prepared via VIC are considerably reduced in comparison with material produced by CIC.

b) The microstructure of γ´ precipitates of both studied materials in as-cast conditions is identical. Heat treatment resulted in the formation of the array of cubes. Low cycle fatigue tests at 800 °C does not further affect the morphology of γ´ precipitates.

c) Low cycle fatigue tests conducted on Inconel 713LC clearly show improvement in fatigue life of material produced via VIC in comparison to CIC material both in the Basquin and Coffin-Manson representation.

d) Heat treatment of vibratory investment casting superalloy resulted in a small increase of fatigue life in the Coffin-Manson representation.

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