

# Durability of MAR-247 and IN-713C Nickel Superalloys under Cyclic Creep Conditions

M. Cieśla\*, F. Binczyk, G. Junak, M. Mańka, P. Gradoń

Faculty of Materials Engineering and Metallurgy, Silesian University of Technology,  
Kraśińskiego 8, 40-019 Katowice, Poland

\*Corresponding author. E-mail address: marek.ciesla@polsl.pl

Received 11.06.2015; accepted in revised form 15.07.2015

## Abstract

Paper presents the assessment of impact of heat treatment on durability in low-cycle fatigue conditions (under constant load) in castings made using post-production scrap of MAR-247 and IN-713C superalloys. Castings were obtained using modification and filtration methods. Additionally, casting made of MAR-247 were subjected to heat treatment consisting of solution treatment and subsequent aging. During low-cycle fatigue test the cyclic creep process were observed. It was demonstrated that the fine-grained samples have significantly higher durability in test conditions and, at the same time, lower values of plastic deformation to rupture  $\Delta\epsilon_{pl}$ . It has been also proven that durability of fine-grained MAR-247 samples can be further raised by about 60% using aforementioned heat treatment.

**Keywords:** Nickel superalloys, Macrostructure modification, Heat treatment, Low-cycle fatigue, Cyclic creep

## 1. Introduction

Creep-resisting Ni-based casting superalloys, i.e. MAR-247 and IN-713C, are primary materials used for manufacturing of critical parts for aircraft jet engines like the turbine blades. These alloys are precipitation hardened and develop specific structure during solidification consisting of equiaxed, frozen and columnar grains. This structure may lead to premature failure of turbine parts, so it is imperative to use modification treatment during casting process to eliminate the undesired grain types leaving only equiaxed ones [1-5].

One of the main problems in casting technology of creep-resisting Ni-based alloys is a the possibility to of obtaining products characterised with by the required grain size for specified working conditions of these products. From the point of view of performance of the castings it is most desirable to optimally combine their creep and thermo-mechanical fatigue resistance with plasticity. This advantageous set of properties may be achieved for example by proper selection of the size,

orientation and homogeneity of the grain. The resistance of nickel superalloy in time increases along with the grain size of the grain, while its yield stress and tensile strength usually decrease.

Methods that enable control of grain size in creep-resisting Ni-based casting alloys include mainly: surface modification, bulk modification of liquid alloy and subjecting the solidifying alloy to mechanical factors [6-11].

The efficient application of high-temperature creep resistance materials requires knowledge about the creep mechanisms prevailing under certain conditions [12-14]. In the case of cast nickel superalloys, the assessment of impact of the chemical composition of superalloys, conditions of processes of their casting process conditions and modification process, which determine the morphological characteristics of macro- and micro-structure, on the durability under creep conditions is of particular importance. These tests provide information on material behaviour in extreme operating conditions [15-20].

The paper presents the assessment of the impact of surface and bulk modification and dual filtration during pouring into moulds on the durability under accelerated creep conditions of

castings made from post-production scrap of MAR-247 and IN-713C superalloys. Cyclic creep process were observed during low-cycle fatigue tests using MTS-810 machine in high temperature and under constant maximum load. Also, the impact of heat treatment (solution treatment and aging) on creep durability of the obtained castings of MAR-247 was examined.

## 2. Materials and methods of investigation

Samples for mechanical testing were prepared from castings made of post-production scrap of MAR-247 and IN-713C superalloys. The castings were produced in the following two casting experiments:

1. blue modifying mould and blue modifying filter,
2. white non-modifying mould and blue modifying filter.

Re-melting process of post-production scrap in  $Al_2O_3$  crucible followed by casting has been performed in Leybold-Heraeus vacuum induction furnace of the type IS 5/III. In the experiment 1, macrostructure of material was formed in conditions of combined bulk and surface modification treatment. Whereas in the experiment 2, macrostructure of material was formed in conditions of bulk modification treatment only. The combined treatment consisting of surface and bulk modification requires the use of so called "blue" mould (with  $CoAl_2O_4$  cobalt aluminate coating) and placement of modifying filter (also containing the cobalt aluminate) in the gating system of the mould. [7,10,11].

Some of the obtained MAR-247 castings were subjected to heat treatment consisting of solution treatment in  $1185\text{ }^\circ\text{C}$  for 2 hours and subsequent aging in  $879\text{ }^\circ\text{C}$  for 20 hours.

Three groups of samples of dimensions shown on Fig. 1 were prepared from castings according to procedures for low-cycle fatigue tests (Table 1).

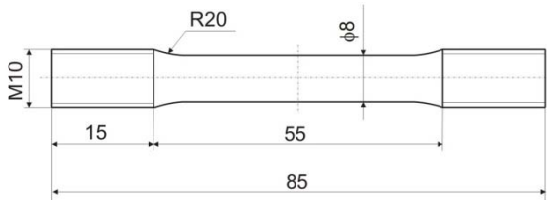


Fig. 1. Dimensions of fatigue test sample.

First two groups consisted of MAR-247 samples. First group consisted of samples 1 and 2 obtained in, respectively, experiments 2 and 1. Second group contained sample 3 made from casting obtained in experiment 2 and subjected to heat treatment. Third group consisted of samples 4 and 5 made of IN-713C obtained in, respectively, experiments 2 and 1.

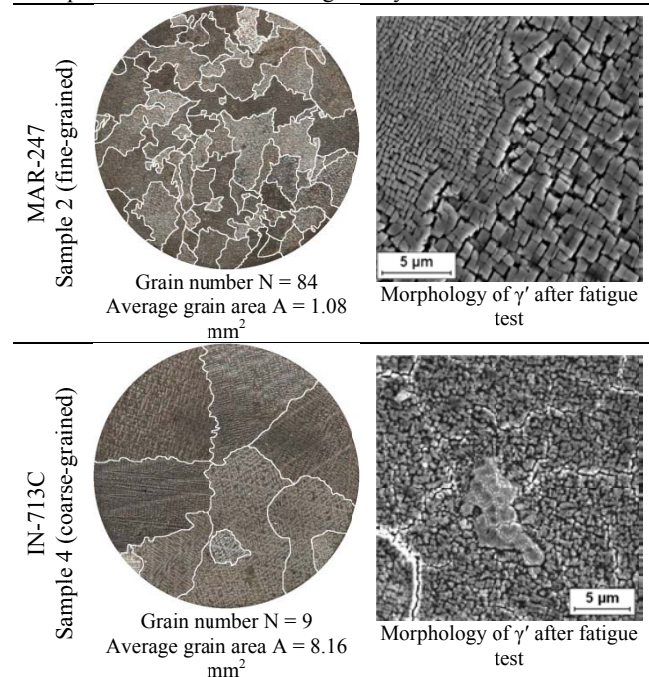
The macrostructure examination shows that the use of combined surface and bulk modification (blue modifying mould and blue modifying filter) leads to fine-grained structure. Whereas application of bulk only modification (non-modifying mould and blue modifying filter) leads to coarse-grained structure. Thus, in

conducted experiments, the bulk only modification treatment did not play a noticeable role in grain size control.

Table 1. Macrostructure morphology of MAR-247 and IN-713C

No	Material	State	Grains on cross-section	Average grain area [ $\text{mm}^2$ ]
1	MAR-247	as cast	17	4.36
2			84	1.08
3			after HT	24
4	IN-713C	as cast	9	8.16
5			47	1.96

Table 2. Examples of macrostructure image analysis



Low-cycle fatigue tests in high temperature for MAR-247 and IN-713C superalloys were performed on MTS-810 machine using parameters presented in Table 3. These parameters, different for every alloy, were selected to simulate extreme operating conditions. Threaded cylindrical samples (Fig. 1) were heated by induction. Fatigue test were realized using 0.1 Hz frequency and rate of asymmetry  $R = 0.1$  under constant load  $\Delta\sigma$  (Fig. 2 and 3).

### 3. The results and discussion

The so called cyclic creep were observed during low-cycle creep tests (Fig. 2 and 3). This is one of the deformation processes commonly seen in critical parts of jet engine turbines.

Analysis of the results of creep tests presented in Table 1 shows that the fine-grained samples of MAR-247 and IN-713C

superalloys have significantly higher durability in as cast state in comparison to coarse grained samples (respectively about 10 and 50 % higher). In addition to higher durability these samples had also significantly lower creep deformation  $\Delta\epsilon_{pl}$  (Table 3). This effect is probably related to higher deformation strengthening of fine-grained materials.

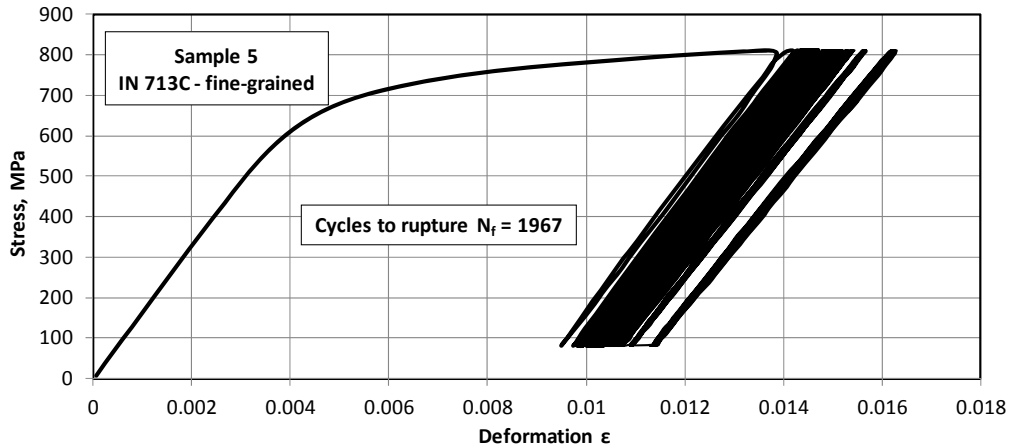


Fig. 2. Cyclic creep curve for IN-713C

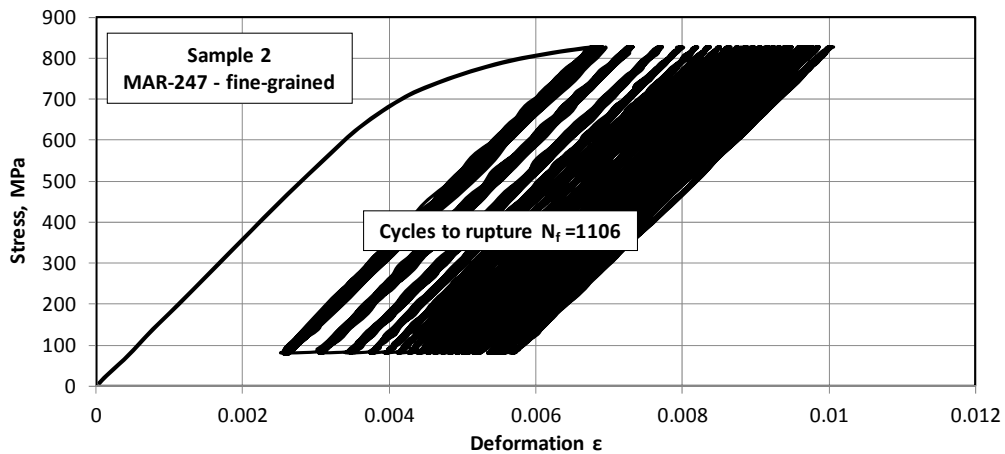


Fig. 3. Cyclic creep curve for MAR-247C

Table 3. Results of low-cycle fatigue tests for MAR-247 and IN-713C alloys

No	Material	State	Test temp. [°C]	$\sigma_{max}$ [MPa]	$R_{p0.2}$ [MPa]	$\sigma_{max}/R_{p0.2}$	Cycles to rupture $N_f$	Creep deformation $\Delta\epsilon_{pl}$
1	MAR-247	as cast	760	830	773.1	1.07	984	0.0104
2		after HT			810.9	1.02	1106	0.0053
3		822.8			1.01	1594	0.0063	
4	IN-713C	as cast	700	810	715.4	1.13	1324	0.0172
5					724.2	1.12	1967	0.0110

The heat treatment of MAR-247 samples resulted in an 60 % increase in durability compared to as cast state. This effect is probably caused by high fragmentation of  $\gamma'$  phase (Fig. 4a) resulting from heat treatment, which, in turn, positively influenced the deformation strengthening effect, raised the  $R_{p0.2}$  and significantly lowered plastic creep deformation  $\Delta\epsilon_{pl}$  in cyclic creep process (Table 3). The cracking process of samples used in experiments were initiated on the surface and propagated mainly along grain boundaries (Fig. 4b)

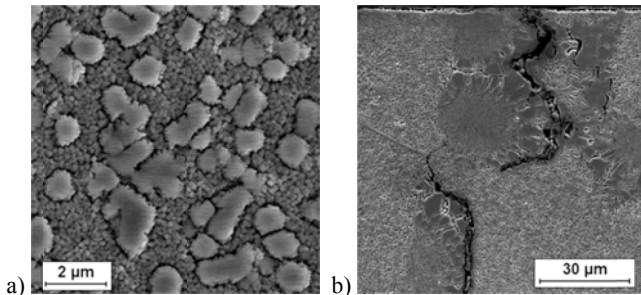


Fig. 4. Microstructure of MAR-247 alloy: a) after heat treatment and fatigue test (sample 3), b) after fatigue test (sample 2)

## Acknowledgements

Financial support of Structural Funds in the Operational Programme - Innovative Economy (IE OP) financed from the European Regional Development Fund - Project "Modern material technologies in aerospace industry", Nr POIG.01.01.02-00-015/08-00 is gratefully acknowledged.

## References

- [1] Seon-gab, K., Young-ha, H., Tae-gu K. & Chang-min, S. (2008). Failure analysis of J85 engine turbine blades. *Engineering Failure Analysis*. 15, 94-400.
- [2] Haijun, T., Dashu C., Hongyu, Y., Mingli, X. & Ruichun, D. (2009). Fretting fatigue failure of an aero engine turbine blade. *Engineering Failure Analysis*. 16. 2004-2008.
- [3] Strang, A. (1980). High Temperature Properties of Coated Superalloys, Behaviour of High Temperature Alloys in Aggressive Environments. *The Metals Society*. London, UK 595-611.
- [4] Zielińska, M. Sieniawski, J. & Wierzbińska, M. (2008). Effect of modification on microstructure and mechanical properties of cobalt casting superalloy. *Archives of Metallurgy and Materials*. 53(3), 887-893.
- [5] Binczyk, F. & Śleziona, J. (2010). Effect of modification on the mechanical properties of IN-713C alloy. *Archives of Foundry Engineering*. 10(1), 195-198.
- [6] Xiong, Y., Yang, A., Guo, Y., Liu, W. & Liu, L. (2001). Grain refinement of superalloys K3 and K4169 by the addition of refiners. *Science and Technology of Advanced Materials*. 2. 13-17.
- [7] Binczyk, F., Śleziona, J. Gradoń, P. (2011). Modification of the macrostructure of nickel superalloys with cobalt nanoparticles. *Composites*. 1, 49-55.
- [8] Xiong, Y., Du, J., Wie, X., Yang, A. & Liu, L. (2004). Grain refinement of Superalloy IN 718C by the addition of Inoculants. *Metallurgical and Materials Transactions A*. 35A, July. 2111-2114.
- [9] Binczyk, F. & Śleziona, J. (2010). The ATD thermal analysis of selected nickel superalloys. *Archives of Foundry Engineering*. 10(2), 13-19.
- [10] Cieśla, M., Binczyk, F. & Mańka, M. (2012). Impact of surface and volume modification of nickel superalloys IN-713C and MAR-247 on high temperature creep resistance. *Archives of Foundry Engineering*. 12(4), 17-24
- [11] Binczyk, F., Gradoń, P. & Mańka, M. (2012). Mechanical Properties And Creep Resistance of Nickel Alloys After Complex Modification And Double Filtration. *Archives of Foundry Engineering*. 12(2), 5-8.
- [12] Frost, H.J., Ashby, M.F. (1982). Deformation-Mechanism Maps. The plasticity and creep of metals and ceramics, Oxford, Pergamon press 166.
- [13] Nabarro, F.R.N., Cress, C.M. & Kotschy, P. (1996). Thermodynamic driving force for rafting in superalloys. *Acta materialia* 44. 3189-3198.
- [14] Epishin, A. & Link, T. (2004). Mechanism of high temperature creep of nickel-based superalloys under low applied stresses. *Philosophical Magazine*. 84. 1979-20
- [15] Cieśla, M. (2009). Durability of ZS6U nickel superalloy with aluminide protective layer in thermal and mechanical load conditions, Monograph, Editor: Wydawnictwo Pol. Śl. (in Polish).
- [16] Okrajni, J., Cieśla, M. & Swadźba, L. (1998). High-Temperature Low-Cycle Fatigue and Creep Behaviour of Nickel-Based Superalloys with Heat-Resistant Coatings. *Fatigue and Fracture of Materials and Engineering Structures*. 21, 947-954.
- [17] Castillo, R., Koul, A.K. Inmarigeon, J-P. (1988). The Effects of Service Exposure on the Creep Properties of Cast IN-738LC Subjected to Low Stress High Temperature Creep Conditions, Superalloys 88, S. Reichman, D.N. Duhl, G. Maurer, S. Antolovich, C. Lund, Eds., The Metallurgical Society.
- [18] Zielińska, M., Sieniawski, J. & Poreba, M. (2007). Microstructure and mechanical properties of high temperature creep resisting superalloy Rene 77 modified  $CoAl_2O_4$ . *Archives of Materials Science and Engineering*. 28(10), 629-632.
- [19] Wyrzykowski, J., Pleszakow, E., Sieniawski, J. (1999). Deformation and cracking of metals. WNT Warszawa (in Polish).
- [20] Bernsztejn, M.L. Zajmowski, W.A. (1973). *Structure and mechanical properties of metals*, WNT Warszawa (in Polish)