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Role of defects in fatigue damage mechanisms of cast polycrystalline superalloy MAR-M 247

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Abstract. High-cycle fatigue life of nickel-based superalloy MAR-M 247 was experimentally determined for as-cast material and material processed by hot isostatic pressing (HIP). Fatigue testing was conducted at temperatures 650, 800, 900 °C in laboratory air. HIP was done at the following conditions: 1200 °C/100 MPa/240 min. It has been found that HIP significantly improves the fatigue life. Obtained results indicate that main factors which determine the fatigue strength of material in both conditions are grain size, grain orientation and size and distribution of casting defects. The distribution and size of the casting defects were evaluated by light microscopy on metallographic sections. The data were processed by the extreme value statistics, which enables to estimate the maximum size of a defect likely to occur in a defined volume. Light and scanning electron microscopy were used for fractographic investigation of fracture surfaces and fatigue crack initiation sites. Focused ion beam technique and transmission electron microscopy were applied with the aim to reveal the microstructure in the nearest vicinity of the early cracks. The mechanism of crack initiation, early crack propagation and the role of casting defects were described and discussed.

The alloy MAR-M 247 is cast polycrystalline nickel-base superalloy developed by Martin Marietta Corporation. The alloy belongs among advanced cast superalloys with exceptionally high temperature strength, corrosion and oxidation resistance. Thanks to balanced chemical composition the alloy exhibits very good microstructural and mechanical stability up to temperatures of 1000 °C.

Chemical composition of the alloy was following (in wt. %): 0.15 C, 8.37 Cr, 0.67 Mo, 5.42 Al, 1.01 Ti, 3.05 Ta, 9.92W, 9.91 Co, 0.04 Nb, 0.015 Br, 1.37 Hf, bal. Ni. HIP procedure is used for cast materials with the aim to close or at least minimalize casting porosity. Therefore one batch of the material underwent HIP procedure while second one was left in as-cast state. Subsequently, both batches were heat treated by solution annealing (1200 °C/2 hours) and then by precipitation annealing (870 °C/24 hours). The structure of the MAR-M 247 alloy is dendritic with coarse grains of average size 0.8 mm. Casting defects were detected in the structure. Their typical size was around 400 μm measured in alloy after HIP, while pores over 1 mm were found in the alloy without HIP. High volume fraction (approximately 60%) of strengthening phase γ' is heterogeneously distributed in γ matrix. Areas of fine γ' precipitates with mostly cuboidal shape (edge size 0.4 μm) are often surrounded by areas of coarse γ' precipitates (1.6 μm in diameter) of spherical or more complicated morphologies. Numerous carbides and eutectics γ/γ' were found in interdendritic and grain boundary areas.

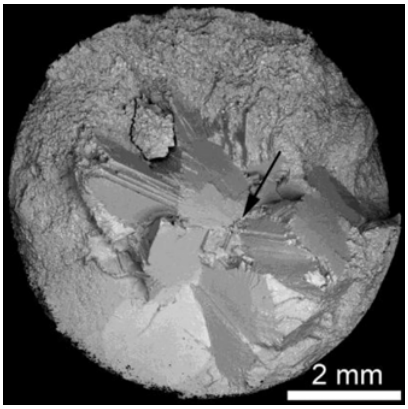

Figure 1. Crystallographic fatigue fracture surface of specimen cycled at 650 °C, ($\sigma_a = 220$ MPa, $N_f = 2.0 \times 10^6$). The fatigue crack initiation site is marked by arrow.

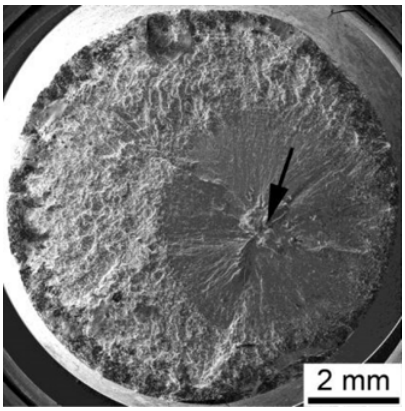

Figure 2. Non-crystallographic fatigue fracture surface of specimen cycled at 900 °C, ($\sigma_a = 220$ MPa, $N_f = 6.51 \times 10^5$). The fatigue crack initiation site is marked by arrow.

Resonant testing machine with 100 kN force range was used for fatigue tests under load control regime in fully reversed loading (R = −1). The frequency of loading was around 122 Hz. Cylindrical specimens with cylindrical gauge (8 mm in diameter and 23 mm in length) were used in the study. The experimental temperature was provided by electric furnace with resistance heating. All tests were done in laboratory air.

The fracture surfaces and specimens cross-sections were observed by scanning electron microscopy (SEM) equipped by electron back scatter diffraction (EBSD) detector and also by light microscope (LM) with image analysis software.

The S-N curves in high cycle fatigue region were obtained for the alloy which underwent HIP procedure as well as for the alloy without HIP. The test temperatures were 650, 800 and 900 °C. The results clearly show that HIP has significant influence on the fatigue performance of the alloy. The material without HIP procedure had significantly worse high fatigue resistance than the alloy after this procedure.

Fractographic analysis revealed that shrinkage pores are main fatigue crack initiation sites in the most cases. The size and distribution of the pores is strongly heterogeneous and fluctuate significantly. Therefore numerous specimen sections were metallographically analysed and processed by extreme value statistics.

The fatigue fracture surfaces revealed changes in appearance due to the increase of the test temperature. Crystallographic fatigue crack propagation with characteristic facets on the surface was dominant for tests at 650 °C (see Fig. 1). Observation of longitudinal cross-sections of specimens revealed intensive cyclic slip activity along the activated shear planes. EBSD analysis confirmed that these planes are of (111) type. Extend of crystallographic crack propagation was significantly lower at temperature 800 °C. The facets appeared just in the vicinity of the crack initiation sites and from a certain distance the fatigue crack propagated by non-crystallographic mode macroscopically perpendicularly to the loading axis. This mode of fatigue damage was dominant even in areas around crack initiation site at temperature 900 °C (see Fig. 2). This change of the fracture surface appearance is mainly caused by emergence of thermally activated processes in structure like diffusion and dislocation climb and cross-slip.

SEM observations, focused ion beam technique and transmission electron microscopy were used to analyze areas in front of the crack tip. Strong cyclic slip activity going across matrix channels as well as γ' precipitates was observed.

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