Materials Science & Engineering A 618 (2014) 578–585

Contents lists available at ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Comparison of microstructural crack paths between hypo-eutectic Al–Si–Cu and Al–Si–Mg cast alloys in high plasticity regimes under rotating bending

Patrik Huter [a,*], Gerhard Winter [a], Martin Schwab [a], Philipp Renhart [a], Stefan Oberfrank [a], Florian Grün [a], Bernhard Stauder [b]

[a] Chair of Mechanical Engineering, Montanuniversitaet Leoben, Franz-Josef-Strasse 18, 8700 Leoben, Austria
[b] Nemak Linz GmbH, Zeppelinstrasse 24, 4030 Linz, Austria

ARTICLE INFO

Article history:
Received 2 May 2014
Received in revised form
18 August 2014
Accepted 24 August 2014
Available online 16 September 2014

Keywords:
Microstructural cracks
Fatigue
In situ crack observation
Crack path
Rotating bending
Aluminium cast alloy

ABSTRACT

It is nowadays widely recognized that good and profound knowledge of the deformation behavior and/or crack propagation behavior is a vital part of high performance simulation for advanced high stress fatigue life prediction. Concerning of those two different approaches, one must, however, be aware that additional and detailed information of fatigue induced crack nucleation, its further propagation path and the associated crack growth rate is important for the intrinsic understanding of the material damage process.

This paper investigates how the fatigue process works in high stressed Al–Si–Mg and Al–Si–Cu fatigue samples starting from crack nucleation to sample rupture by rotating bending loads at room temperature. The samples themselves were taken directly from serial casted and heat treated cylinder head components and were processed to conventional hourglass specimens. Because no suitable test method which fulfils all the necessary test requirements was commercially available, a new rotating bending testing machine which directly operates in a confocal light microscope was developed. This test method allowed us to easily compare every change of the crack growth rate (especially for microstructural small cracks) with the microstructure and its crack path. At high stress regimes eutectic phases became very important for fatigue induced crack nucleation and early crack propagation. In the first third of the lifetime, both alloys cracked on multiple spots by interface cracking between hard phase particles (β-phase) and eutectic matrix. Depending on the crack length and stress intensity factor ΔK proceeding cracks were also able to move into the dentritic matrix (α-phase). At the end of the lifetime only a fraction of all nucleated cracks of each specimen became large enough to exert influence for fatigue failure.

Furthermore, using this test method as an integral element of stress gradient fatigue investigation makes it possible to identify and define major microstructural crack relevant objects like particles during material fatigue. Hence, it not only increases the knowledge for high performance fatigue simulation but also provides a tool for material optimization by fatigue processes themselves.

1. Introduction

For a comprehensive understanding of fatigue behavior the influence of microstructure on crack initiation and propagation in addition to conventional fatigue strength is important for fatigue life estimation. Therefore, information on microstructural sites of crack initiation and on the characteristics of crack paths for the different stages of crack growth is needed. The coupling of the microstructure with crack behaviour from nucleation to fracture is advisable. This would offer component manufacturers in particular a powerful tool to further develop the process regarding the produced microstructure to describe crack paths. Actually standardized fracture mechanic tests use pre-scratched specimens to describe crack paths. This method of investigation provides only insufficient information on crack initiation and its microstructural propagation, especially when components spend most of their lifetime in such a small crack state.

* Corresponding author. Tel.: +43 3842 402 1464.
E-mail addresses: patrik.huter@unileoben.ac.at (P. Huter), gerhard.winter@unileoben.ac.at (G. Winter), martin-albin-andreas.schwab@stud.unileoben.ac.at (M. Schwab), philipp.renhart@stud.unileoben.ac.at (P. Renhart), stefan.oberfrank@stud.unileoben.ac.at (S. Oberfrank), florian.gruen@unileoben.ac.at (F. Grün), bernhard.stauder@nemak.com (B. Stauder).

http://dx.doi.org/10.1016/j.msea.2014.08.062
0921-5093/

In this paper, hypo-eutectic Al–Si casting alloys that are mainly used for automotive cylinder heads were observed. Previous investigations underline the impact of dentrite arm spacing, which depends on cooling rates and the strontium content of Al–Si–Cu systems [1], on fatigue properties [2,3], especially for uniaxial tension–compression tests. The direct relationship between the short crack behaviour and the microstructure of Al–Si alloys was previously carried out under considerable experimental effort, even though for hypereutectic casting Al–Si systems [4]. It underlines the importance of the microstructure particularly for short crack damaging and hence, to understand the fatigue damaging in this stress regimes. Furthermore, structural stress gradients appear through local notches in real components, which requires additional material testing with stress gradients like rotating bending or using notched specimens [5,6] to understand the complex interaction in components. Hence, by default, rotating bending investigations are an integral part of standard fatigue life evaluation with structural gradient loadings. But conventional rotating bending fatigue tests provide incomplete information of crack initiation and only by extensive post-mortem fractographic analysis. In order to observe the in situ crack behaviour under rotating bending a test system, which meets the necessary requirements like fatigue associated crack nucleation, multiple crack tracking, high testing frequencies, high positioning resolution and the availability of testing default sized specimens and material independence must be used.

In general, most optical crack tracking systems are SEM based. The specimen is mounted into a fatigue servo system in a vacuum camber [7,8]. Hence it is possible to observe the fatigue process of a specimen in size of $14 \times 2.5 \times 2.3$ mm by 0.01 Hz recording. Between the crack recording steps, the fatigue process is pushed forward by 2 Hz pulsing. With advanced modifications it becomes possible to apply a fatigue system for high loadings of about ± 5 kN or increased test frequencies up to 10 Hz by using servo-hydraulic test systems in the vacuum chamber [9,10] in the SEM system. The problem of all SEM fatigue systems is the lack of macro-scale observations. Most observations are limited to a small gauge area of a few square millimetres.

In situ crack observations based on light microscopy or camera systems may have a larger gauge area with lower magnification, but at the same time, they have higher flexibility in the field of application like the extraordinary observing of corrosion induced cracks in high temperature water by a 4×10 mm gauge area [11]. All of those presented methods are not suitable for rotational bending tests. Only a coherent interaction between stroboscope, testing frequency and a triggered camera or microscope observing makes in situ crack observation possible for rotating bending but are restricted to single or few crack analysis [12,13].

On the other hand, the technique of semi-in situ crack observation provides the most flexible solution for testing and observation because material testing and observation are done completely separated. The fatigue step can be achieved on conventional test rigs with macroscopic specimens. The main drawbacks are the laborious mounting and demounting steps and the transfer into the analysis system, such as light or scanning electron microscopy [14,15].

This paper introduces a testing method to figure out how small cracks nucleate and propagate under rotating bending by semi-in situ analysis. The cracks are tracked from nucleation to the specimen's failure with much less effort than other systems. With this test method, which is also part of interest and discussion, two common hypo-eutectic Al–Si casting alloys used for cylinder heads were compared by their crack behavior and its propagation paths.

2. Experimental methods

The challenge of observing multiple fatigue initiated cracks with the microscope aided rotating bending system and the lack of current commercial products, a new testing machine was designed. It was a consequent development of the manual mounting and test procedures as described in [15]. The confocal laser microscope Olympus LEXT and the test rig was unified into one unit for ambient air and room temperature by this system. A direct operation under the microscope was realized allowing semi-in situ observations with no intermediate mounting steps. The construction, a miniature rotating bending machine (Mini-RB) was built with the dimensions $335 \times 65 \times 58$ mm. In Fig. 1a a wire model and the main components are shown. The static system was based on a 3-point bending system but the round hourglass fatigue specimen forced the overlap of maximum stress and the area of observation. The negative interfering of lateral forces applied by 3-point bending was less than 5% of total stress loading by the optimized fulcrum geometry. The mounted step motor was able to perform 10 Hz testing frequencies by increments of less than 0.1°, allowing high precise reproductive crack tracking. The lift of the calotte component onto the floating bearing was redirected by the swing arm.

By the way all the cracks were always opened on the specimen's upside, which allowed more comfortable crack analysis. The crack length was measured by confocal stacked photography from the microscope's internal acquisition system. The total and transversal projected crack length was monitored for further evaluation methods. For stress controlled tests the loading force and hence the bending moment were online controlled. More details can be found in [16,17]. A complete intrinsic multiple automatized crack detection system by resonance analysis is nowadays subject to more theoretical work but fails in real heterogeneous microstructures and for multiple microstructural crack formations [18–20]. Here, a more deterministic defined observation method was used.

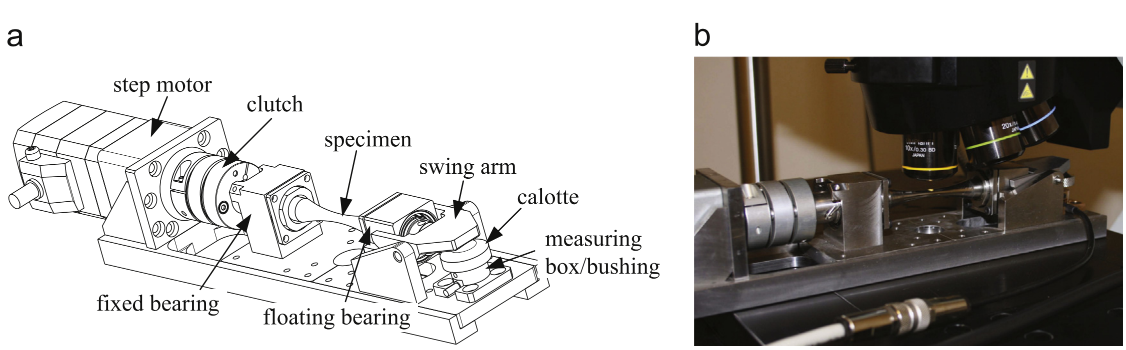

Fig. 1. New design of rotating bending test system for quantitative microstructural crack observations. (a) Wire model of the miniature rotating bending machine and (b) Miniature bending machine in operational conditions under the confocal laser microscope Olympus LEXT.