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Materials Science and Engineering A 460–461 (2007) 20–30

MATERIALS SCIENCE & ENGINEERING A

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A through process model of the impact of in-service loading, residual stress, and microstructure on the final fatigue life of an A356 automotive wheel

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Received 5 November 2006; accepted 16 January 2007

Abstract

Fatigue life is a key consideration in the design of cast aluminium alloy automotive wheels. In this investigation, a through process modelling methodology was used to predict the fatigue life of an A356 automotive wheel subject to bending fatigue. This methodology considers the evolution of microstructural features and stress state through the manufacturing process (including casting, heat treatment, and machining) and during service loading. This paper focuses on validating the in-service model and quantifying the interaction between the key factors influencing fatigue behaviour. The cyclic elastic strains measured on the wheel surface for a series of different bending loads were found to agree well with predictions. The predicted crack initiation sites and the number of cycles to cause failure in the wheel were in agreement with full scale fatigue tests on wheels. The fatigue life and associated scatter are shown to be a function of microstructure, residual stress and in-service loading. Both the pore size and loading level have a significant impact on fatigue behaviour, while residual stresses showed a moderate influence on fatigue life for the wheel.

Keywords: Through process modelling; Microstructure prediction; Casting; Heat treatment; Stress analysis; Aluminium alloys; Fatigue life

1. Introduction

In transport applications, components manufactured from cast aluminium alloys offer an improved strength-to-weight ratio and better fuel efficiency relative to ferrous alloys. The cyclic nature of in-service loading in some applications makes fatigue performance a key design consideration. A predictive tool is required to assist in design from a fatigue perspective. The fatigue life of a component is intrinsically determined by alloy composition, microstructural features, and the presence and size of defects. Extrinsic factors such as residual stress and in-service loading also influence fatigue life. For cast aluminium alloy components, the manufacturing process, comprised of casting, heat treatment (including solution, quenching and artificial ageing steps) and machining, influences the intrinsic fatigue strength and the residual stress state. Therefore, the required predictive tool should link the influence of the manufacturing process with in-service loading to predict the final fatigue behaviour of the component, termed through process modelling [1]. Each of the critical manufacturing sub-processes is linked to an overall service model that incorporates the key intrinsic and extrinsic factors (as shown in Fig. 1).

The first step in this methodology, corresponding to the first stage of manufacturing, is the development of a casting model to predict microstructural features and defects, such as secondary dendrite arm spacing and porosity. The second step is to simulate the T6 heat treatment to predict the residual stress distribution developed during quenching. In the third step, the residual stress relief occurring upon removal of a layer of surface material during machining is predicted. The fourth step focuses on the in-service behaviour, predicting the stress state arising from the applied cyclic load and the residual stress. In the final step, the performance is predicted by linking the microstructural features and stress state in fatigue life calculations.

In previous studies, the authors have demonstrated the viability of the through process modelling methodology, validating separately the casting [2], residual stress [3], and fatigue [4–6] components. However, the application of this methodology

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doi:10.1016/j.msea.2007.01.076

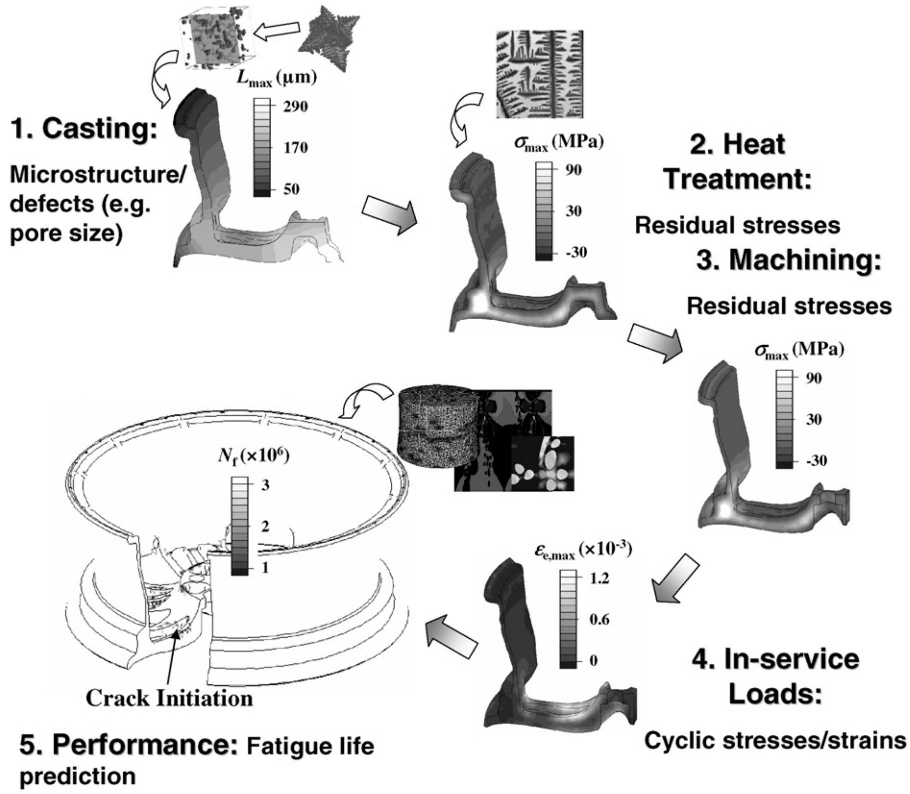

Fig. 1. Schematic of multiscale through process modelling methodology used to predict fatigue life.

to an aluminium alloy wheel including in-service loading has not been reported. A few authors have predicted the variation of stress in a wheel due to service loads during radial [7] or bending [8–10] fatigue tests. However, these studies did not incorporate the residual stress distribution resulting from manufacturing, which is necessary to calculate the in-service stress distribution.

In the current investigation, a validated in-service stress model of a bending fatigue test employed to assess A356 automotive wheels was linked with a previously reported through process model. This allowed the interaction of the key factors affecting fatigue behaviour to be quantified. The prediction of in-service cyclic strain variation under different bending loads is compared with experimental measurements of strain. The predicted fatigue lives of wheels tested at different loads are validated against bending fatigue test data.

2. Experimental methodology

2.1. Bending fatigue test

The bending fatigue test (SAE J328, Fig. 2) is used by some wheel manufacturers to assess the fatigue performance of wheels for loading conditions that are consistent with cornering (bending moment applied during continuous rotation). This test is part of standard operating practice to periodically assess product quality and qualify new designs. The inboard rim flange is centred and clamped securely to a rotating table. A rigid shaft is then attached to the hub section of the wheel and fastened using bolts tightened to a specified torque. The shaft weight is compensated for in the test machine such that there is no axial load on the test wheel. Three load levels (2.4, 3.6, 4.2 ± 3% kN) were applied in a direction perpendicular to the length of the shaft and 1 m below the wheel hub providing a constant bending moment. The shaft was rotated at 240 rpm to produce a cyclic bending load.

2.2. Cyclic strain measurements

The elastic strains arising in the bending fatigue tests were measured at three locations in the same spoke of a finished wheel. The locations were selected based on model peak strain predictions. The wheel (∼480 mm diameter) was instrumented with HBM™[1] aluminium compensated, rectangular rosette strain gauges to facilitate the determination of the principal strains. The gauges were bonded following a standardised procedure of surface preparation [3]. The strain measurements were conducted using a STRAINSERT™,[2] TN8C strain indicator employing a quarter-bridge circuit configuration.

Prior to mounting the instrumented wheel on the bending fatigue test machine, strain measurements were performed to determine the effect of bolt torque. The wheel was mounted and the baseline strains were measured. The bending load was

[1] HBM is a registered trademark of HBM GmbH, Darmstadt, Germany.
[2] STRAINSERT is a registered trademark of Strainsert Co., West Conshocken, PA, USA.