International Journal of Fatigue 74 (2015) 38–45

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Validation of a high-cycle fatigue model via calculation/test comparisons at structural scale: Application to copper alloy sand-cast ship propellers

Anthony Ezanno [a,b], Cédric Doudard [a,*], Sylvain Moyne [a], Sylvain Calloch [a], Thierry Millot [c], David Bellèvre [d]

[a] *Laboratoire Brestois de Mécanique et des Systèmes – LBMS EA4325, ENSTA Bretagne/UBO/ENIB, 2 rue François Verny, 29806 Brest, France*
[b] *DGA Techniques navales, Avenue de la Tour Royale, BP 40915, F-83050 Toulon Cedex, France*
[c] *DCNS Centre de Nantes – CESMAN, Indret, 44620 La Montagne, France*
[d] *DGA Techniques hydrodynamiques, 27105 Val-de-Reuil, France*

ARTICLE INFO

Article history:
Received 24 July 2014
Received in revised form 10 December 2014
Accepted 17 December 2014
Available online 31 December 2014

Keywords:
Probabilistic two-scale model
Crack initiation
Casting defects
Sand cast aluminum bronze
Full-scale fatigue tests

ABSTRACT

An in-house developed software is proposed to study structures made of cast alloy and subjected to high-cycle fatigue. This in-house developed software is based on the implementation of a probabilistic two-scale model for high cycle fatigue life prediction. To validate the proposed approach, calculation/test comparisons at the scale of an engineering component (i.e., copper alloy sand cast ship propellers) have been performed.

So, the first part of the present paper concerns the description of the model for fatigue life prediction and of the fatigue tests performed on two marine propellers. In a second part, the performance of the proposed model is estimated by comparing experimental and theoretical results in the case of full-scale fatigue tests. The results are then discussed and analyzed.

1. Introduction

Fatigue, and more precisely High-Cycle Fatigue (HCF), is still one of the main causes of the fracture in service of mechanical engineering components and structures [1,2]. Guaranteeing and ensuring the reliability of mechanical systems in relation to fatigue phenomena is always a difficult question for engineers. Indeed, high-cycle fatigue is an aspect of the mechanics of materials and structures which is particularly insidious because of its progressive and masked character. Moreover, high-cycle fatigue is a complex phenomenon in so far as it depends on a great number of parameters (e.g., chemical composition of the material, microstructure, mechanical loading, environment, temperature, size of the structures...). Over the last few years, significant advances have been made in the comprehension of both microstructural mechanisms of fatigue damage and modeling [2]. Today, a great number of models for fatigue life prediction of materials have been proposed. In the majority of the cases, the models for fatigue life prediction are validated at the scale of Representative Elementary Volume (REV) (i.e., at the scale of fatigue specimen) by showing, for example, their capability to describe or even to predict the *S–N* curves (i.e., amplitude Stress–Number of cycles to failure) of materials.

Engineers and designers often ask themselves the relevant question concerning the capability of the models for fatigue life prediction to predict the fatigue strength of components (i.e., of structures) e.g., [3,4]. It is true that this question is not so easy. There are various reasons for this:

- The first is due to the volume effect e.g., [4–6]. Indeed, the fatigue properties depend on the volume of the specimens that have been used to determine them. The fatigue limit is often lower when it has been determined by using voluminous specimens than when it has been determined by using less voluminous specimens. The passage from the scale of a specimen to the scale of a structure is not so trivial.
- The second is due to the stress heterogeneity effect [4–7]. This effect is observed, for example, when one compares the fatigue limit of a material determined by using tension–compression fatigue tests to the fatigue limit determined by bending fatigue tests. It is generally found that the bending fatigue limit of a material is higher than the tension–compression fatigue limit of the same material [7–10]. One can be faced with such a

---

* Corresponding author. Tel.: +33 2 98 34 89 27; fax: +33 2 98 34 87 30.
E-mail address: cedric.doudard@ensta-bretagne.fr (C. Doudard).

http://dx.doi.org/10.1016/j.ijfatigue.2014.12.008
0142-1123/© 2014 Elsevier Ltd. All rights reserved.

problem when we want to pass from the scale of a specimen to the scale of a structure, because the stress heterogeneity could be very different.

- . . .

Therefore, in this paper we propose to validate a high-cycle fatigue model (already validated at the scale of REV [11]) through calculation/test comparisons at the scale of an engineering component. In this study, particular attention is being paid to large-dimension copper alloy sand cast ship propellers. This case is particularly interesting for several reasons:

- The material, chosen for this study, contains a population of initial micro-flaws due to the casting process.
- The volume difference between the specimens and the component (i.e., ship propeller) is very large.
- The stress heterogeneity in the fatigue specimens and in the component is also very different.
- . . .

The present paper is divided into five parts. The first part is dedicated to the two marine propellers and to the material under study. In the second part of the paper, the constitutive equations of the high-cycle fatigue model are briefly examined [11]. The considered model belongs to the two-scale model family. It has been developed in a probabilistic framework and takes into account the presence of the initial micro-flaws by an indirect approach. The third part of the paper concerns description of the in-house developed fatigue software named "*4Cast*". This in-house developed fatigue software is dedicated to the fatigue life prediction of cast structures. The architecture of the proposed software and the different outputs are presented. In the fourth part of the paper, a full-scale fatigue test campaign on two ship propellers is described. The principle of the fatigue tests on marine propellers is first given. Then, the fatigue tests are performed and validated. After that, the fatigue results are given. In the last part of the paper, the performance of the proposed model is estimated by comparing experimental and theoretical results in the case of full-scale fatigue tests. The results are then discussed and analyzed.

2. The two sand cast ship propellers under study

The two fixed pitch supra-divergent propellers under study come from a patrol boat of the French Navy. Note that the two propellers are prototypes, which have been used for only a few days. It can be considered that they are without mechanical history. Each propeller has four blades. Their diameters measure 1.71 m and weigh approximately 465 kg (Fig. 1).

They are made of a sand cast aluminum bronze CuAl9Ni5Fe4 (i.e., Cupro Aluminum alloy). This alloy is commonly used in marine applications because of its excellent marine corrosion resistance (e.g., [12,13]). Table 1 gives the chemical composition of the studied material.

Fig. 2 shows a typical microstructure of the material. The microstructure consists of a coarse α-phase within a eutectoid $\alpha + \kappa_{III}$ phase where κ_{III}-precipitates are a Ni-rich lamellar-shaped phase. Two other precipitates appear during the slow cooling of the alloy: an Fe-rich rosette-shaped phase (κ_{II}-precipitate) and an Fe-rich κ_{IV}-phase which precipitates finely into the α-grains. More details on the characteristic microstructures of cast copper–aluminum alloys can be found for example in [12,13].

Moreover, as can be seen in Fig. 2, the casting process induces initial flaws in the material such as micro-shrinkage pores. Fig. 3 shows the distribution of defects of identified size on a surface of 100 mm^2. About 800 defects are present on the observed surface. The mean size of this population of defects is close to 16 µm. Table 2 compiles some characteristics of the population of defects.

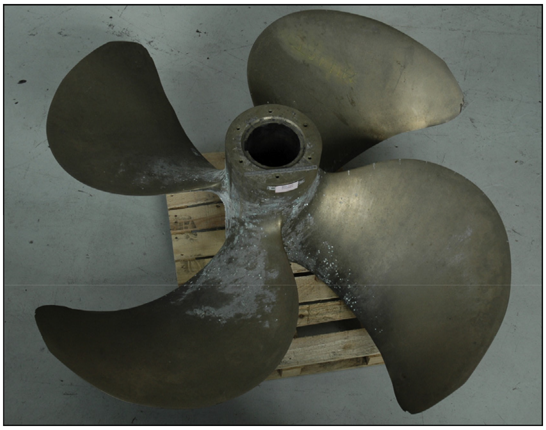

Fig. 1. One of the two fixed pitch supra-divergent propellers under study.

Table 1
Chemical composition of Copper Aluminum (wt%).

Cu	Al	Ni	Fe	Mn
Balance	8.5–10.2	4.0–5.5	3.0–5.5	0–1.5

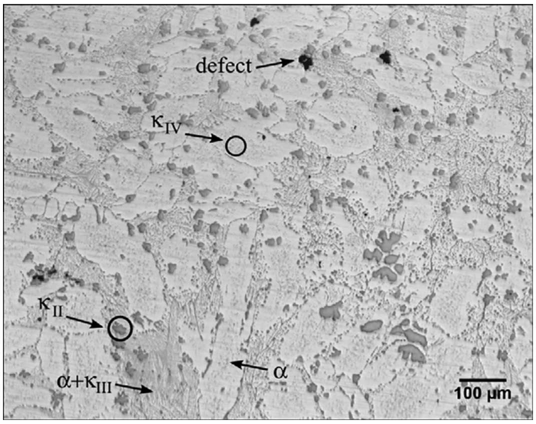

Fig. 2. Optical micrograph of the microstructure of Copper Aluminum alloy.

Obviously, the presence of initial defects in the alloy plays a crucial role in its fatigue life e.g., [14,20]. Nevertheless, in the light of the characteristics of the population of defects present in our material (Table 2), the casting flaws are "invisible" when using classical nondestructive testing methods (i.e., nondestructive testing methods used in a classical industrial context). That is the main reason that an indirect approach was adopted during this work. That means that the characteristics of the population of defects (i.e., size distribution, number of defects, . . .) will not be considered as ingredients of the proposed high-cycle fatigue model [11].

3. A high-cycle fatigue model for cast materials

In this part, the high-cycle fatigue model considered is briefly depicted. Only the necessary and sufficient ingredients for fatigue life determination of a structure are presented. For more details, an interested reader can refer to the reference [11].

As previously stated, the casting process induces the presence of initial micro-flaws in the material. The possible presence of macro-flaws (i.e., detectable by classic nondestructive methods used in an industrial context) in the structure would imply its deposition. In the considered high-cycle model, the presence of