International Journal of Fatigue 110 (2018) 81–94

Contents lists available at ScienceDirect

International Journal of Fatigue

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

HCF of AA7050 alloy containing surface defects: Study of the statistical size effect

Foued Abroug*, Etienne Pessard, Guenaël Germain, Franck Morel

LAMPA, Arts et Métiers ParisTech Angers, 2 Bd du Ronceray, 49035 Angers, France

A R T I C L E I N F O

Keywords:
Surface defect
High cycle fatigue
Kitagawa-Takahashi diagram
Volume effect
Size effect
Weakest link concept
AA7050 alloy

A B S T R A C T

This work investigates the effect of artificial surface defects on the fatigue limit of a 7050 Aluminum alloy (Al Zn6CuMgZr). A large fatigue testing campaign under fully reversed plane bending loading is undertaken on specimen with artificial surface hemispherical defects. The defect number was varied from 1 to 44 defects per specimen and the diameter size ranged from 60 µm to 800 µm. The test results allow the characterization of both the defect effect and scale effect on the fatigue behavior of the material. A probabilistic approach based on the weakest link concept together with a fatigue crack initiation criterion are used to account for the stress distribution and the size of the highly stressed volume. This approach leads to a probabilistic Kitagawa-Takahashi type diagram, which in this case explains the relationship between the defect size and the scale effect on the fatigue strength. The predictions show good agreement with the experimental results and illustrate the importance of taking the scale effect into account when designing components containing different surface defects types or roughness patterns.

1. Introduction

The fatigue data transferability from laboratory specimens to real industrial components or structures is often a tough task due to the high number of parameters affecting the fatigue strength. The loading mode, the microstructural heterogeneities, the defects and residual stresses induced by the manufacturing process, the gradient and the size of the loaded volume are known to greatly affect the fatigue response. For instance, for the same size and geometry of a specimen or a component, it is well known that the loading mode affects the fatigue limit: a difference is usually observed between torsion, uniaxial tension, biaxial tension, rotating or plane bending. These differences can be explained by the stress state and by the macroscopic gradient introduced in the different cases. When extra stress concentrators are introduced (notch, welded joint …), the local gradient is affected and if the critical fatigue area is concerned, the resulting macroscopic fatigue strength can be substantially altered.

It has long been recognized that fatigue limit depends on the spatial stress distribution (volumetric stress distribution) and also on the size of the loaded component. However, the so-called "stress gradient effect" and "size effect" are very closely linked and lead sometimes to confusions. A good review of these two effects was proposed by Papadopoulos and Panoskaltsis [1]. In this paper, the authors try to carefully explain the difference between the pure "size effect" and the pure "stress gradient effect". They clearly show that, very often, the two effects can act concurrently. Let us take the example of a smooth cylindrical specimen submitted to a rotating or plane bending fatigue loading. An increase of the specimen radius leads at the same time to a decrease of the stress gradient and to an increase of the loaded volume. In this case, the two effects are simultaneous. On the contrary, when a smooth cylindrical specimen of constant radius is subjected to a uniaxial tension loading and its length is increased, there is no stress gradient and the stressed volume gets bigger. All the investigations in the literature regarding that kind of experimental studies lead to the well-known conclusions:

— "The higher the gradient, the higher the fatigue strength"
— "The higher the stressed volume, the lower the fatigue strength"

In short, although they are confused in the literature, the two effects are distinct phenomena that need to be accounted for by different approaches.

The models dedicated to the statistical size effect are often of two types. The first type of approach, usually used for nonmetallic inclusions in steel, is based on the extreme value analysis of the inclusion population. It predicts the maximum defect size that is possible to be observed in a given volume [2,3]. The details of the methodology are described in the ASTM standard [4]. The second type of approach

* Corresponding author.
E-mail address: Foued.Abroug@ensam.eu (F. Abroug).

https://doi.org/10.1016/j.ijfatigue.2018.01.012
Received 18 November 2017; Received in revised form 12 January 2018; Accepted 13 January 2018
Available online 31 January 2018
0142-1123/

makes use of a two scale probabilistic model to consider the stressed volume size. Applying the weakest link concept [5], the failure probability of a component is calculated from the failure probability of several elementary volumes [6].

The models dealing with the gradient effect in a deterministic way are often built by using a non local approach like the one initially proposed by Taylor [7,8]. The efficiency of non local approaches has been demonstrated in a number of applications, for instance for notched components [9], specimens containing internal defects [10] or surface defects [11].

Even though several models considering the size effect and the gradient effect are available, just a few of them [12–14] incorporate both effects in a combined manner as discussed in [15]. Moreover, the role of material defects is most of the time investigated by considering the most critical one and by applying a deterministic criterion like in the work of Murakami [2]. The present study aim is to get a better knowledge of the wrought aluminium components considering both statistical size and gradient effects due to the presence of one or several surface defects of different size.

The investigation is both experimental and numerical. Some plane bending fatigue tests are first carried out on specimens showing the same size and geometry but containing one or several identical surface defects. From the experimental results, a Kitagawa-Takahashi diagram is built showing the difference between the 1-defect and x-defects cases. Then the observed specific size effect is modeled by using Finite Element simulations together with the weakest link concept. Two different approaches are tested, surface and volume-based approaches both reflecting a statistical size effect. The suitability and limitations of these approaches are discussed based on the comparisons with experimental results. The main objectives are:

— Characterization of the statistical size effect
— Description of the crack initiation mechanisms with or without the presence of surface defect
— Modeling the size effect

2. AA7050-T7451 alloy and experimental procedure

2.1. The material

The material under investigation is the Al Zn6CuMgZr Aluminum alloy, also called AA 7050. In this study, specimens are machined out of a 30 mm thick sheet. By the local thermomechanical effects induced, machining can change the surface integrity of manufactured parts and therefore change their fatigue strengths. Several studies have shown that in the case of end milled AA7xxx alloys, the geometrical aspect of the surface is the dominant factor on fatigue behaviour [16–18]. Residual stresses as well as the microstructural changes are, in this context, localized to a small thickness layer and will therefore be neglected in the presented study.

The chemical composition of the AA7050-T7451 alloy is given in Table 1. For this range of thickness, the material shows a high recrystallization rate. Areas of consolidation of recrystallized and non-recrystallized grains can reach a few millimeters of length. Grains have dimensions ranging from 5 to 300 µm in rolling and transverse directions, and 5 to 50 µm in depth (see Fig. 1). Different types of intermetallic particles are present at the grain boundaries and in the recrystallized grains (Mg_2Si, Al_7Cu_2Fe, $MgZn_2$, AlCuZn, etc.) (Fig. 2). These particles are brittle and can be at the origin of crack initiation under fatigue loading [18,19].

Table 1
Chemical composition of the AA7050-T7451 alloy, in weight percentage.

Element	Al	Zn	Cu	Mg	Zr	Ti	Si	Fe	Mn
Weight (%)	Bal.	6.027	2.221	1.847	0.102	0.039	0.038	0.095	0.01

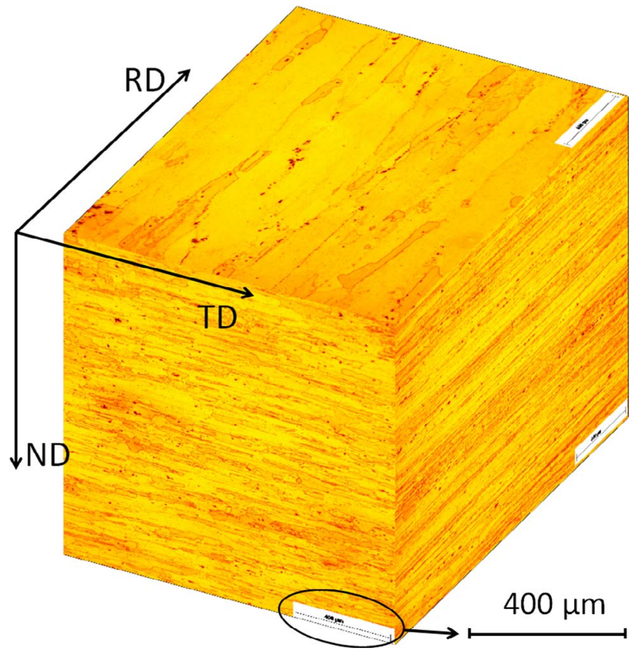

Fig. 1. AA7050-T7451 alloy RD: Rolling Direction, TD: Transverse Direction, ND: Normal Direction.

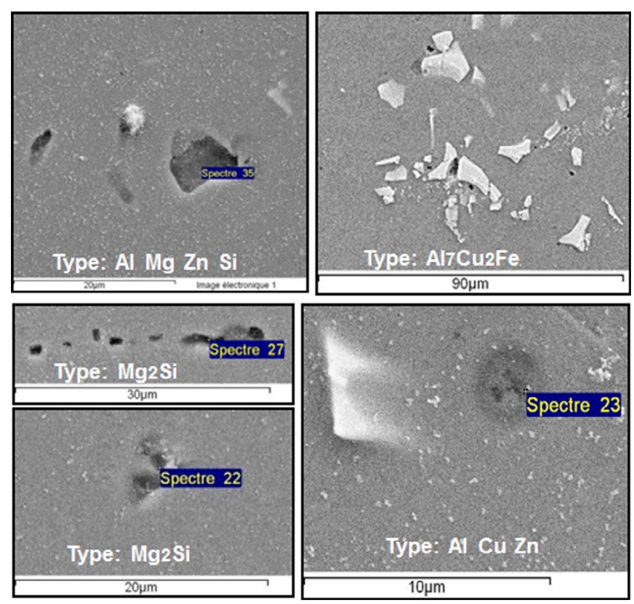

Fig. 2. SEM images of the intermetallic particles observed on the AA7050 alloy sheet.

Table 2
Monotonic properties of the AA7050 alloy.

Rolling direction	Yield stress (MPa)	Ultimate tensile stress (MPa)	Tensile elongation (%)
0°	475	635	12.3
45°	428	496	13.9
90°	475	538	11.9

Monotonic tensile tests are conducted to determine the mechanical properties of the material at 0° , 45° and 90° to the rolling direction (Table 2). Geometry of tensile specimen is shown in Fig. 3. The anisotropy is slightly marked and the ductility is limited with a maximum elongation around 13%. In addition, microhardness measurements are