Materials Science & Engineering A 601 (2014) 116–122

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

On the relationship between elongation and fatigue life in A206-T71 aluminum castings

Murat Tiryakioğlu *

University of North Florida, School of Engineering, 1 UNF Drive, Jacksonville, FL 32224, USA

A R T I C L E I N F O

Article history:
Received 25 January 2014
Received in revised form
10 February 2014
Accepted 11 February 2014
Available online 18 February 2014

Keywords:
Weibull statistics
Quality index
Fatigue life potential

A B S T R A C T

The tensile and fatigue testing results of Staley Jr. et al. [Mater. Sci. Eng. A 460–461 (2007) 324 and Mater. Sci. Eng. A 465 (2007) 136] for A206-T71 castings were reanalyzed. The Weibull distributions for both elongation and fatigue life of castings that were hot isostatically pressed (HIPed) as well as those that received no processing (no-HIP) were correlated. Results indicate that significant improvements in fatigue performance are possible if pores and old oxides are eliminated. Extrapolations of results and underlying mechanisms are also discussed.

1. Introduction

Design concepts are based on the assumption that the maximum stress in an engineered component during its service will be well below the yield strength (σ_Y) of the material selected by the designer. In aerospace castings, in addition to the factor of safety, a casting factor is sometimes required [1], especially in commercial airplanes, to accommodate the scatter in the structural quality of the castings and to ensure that all stresses within the casting are safely below the yield.

Fatigue failure in metals accounts for 90% of all in-service failures due to mechanical causes [2]. Consequently, much effort has gone into determining the mechanisms of fatigue failure, namely crack initiation and propagation before the final rupture. In castings, cracks initiate almost always from defects, such as inclusions and pores [3,4]. It has been only recently understood [5,6] that the degradation of and variability in the mechanical properties of aluminum castings are related to the defects that are introduced into the molten metal usually as a result of poor handling of the molten metal and/or poor filling system design. These defects, namely oxide bifilms, are incorporated into the bulk of the liquid by an entrainment process, in which the surface oxide folds over itself. Unlike steel castings in which the oxide (such as alumina or chromia) has a significantly lower density than the metal thus floating out quickly, leaving the steel clean, the folded aluminum oxide in aluminum has practically neutral buoyancy, so that defects tend to remain in suspension. The layer of air in the folded oxide can grow into a pore, or remain as a crack in the solidified alloy. It has been demonstrated that fatigue life is easily extended by one or two orders of magnitude by improved cleanness of Al alloy castings, and as a consequence it is envisioned [7] that their fatigue performance might be increased by many orders of magnitude when the entrainment defects are minimized or even eliminated. Therefore there is a great potential for processes that are designed to minimize the density and size of these defects.

Although aerospace castings can be considered to be somewhat overdesigned so that stresses are always well below the yield strength, almost all specifications for cast aluminum alloys require a minimum level of elongation as well as yield strength. This elongation requirement can only be interpreted as an expectation for a certain level of structural quality, as evidenced by small number of defects. Therefore elongation specification can be interpreted as a *de facto* fatigue life specification. Although there are a number of publications that link defect size distribution to fatigue life distribution [8,9], to the author's knowledge, there is no study that has addressed the possibility of a link between elongation and fatigue life. This paper is intended to fill that void by reanalyzing data published previously for A206 castings.

2. Experimental details

Staley Jr. et al. [10,11] conducted experiments to determine the effectiveness of various hot isostatic pressing (HIP) conditions on the tensile and fatigue properties of A206 aluminum alloy. Chill cast pig type ingots of A206 were procured for testing since it was expected that ingots produced by conventional

* Fax: +1 904 620 1391.
E-mail address: m.tiryakioglu@unf.edu

http://dx.doi.org/10.1016/j.msea.2014.02.033
0921-5093

processing techniques would exhibit many oxides and much porosity. The chemical composition is given in Table 1. Specimens were excised from ingots that were either hot-isostatically pressed (HIPed) or that did not receive the HIP treatment (no HIP). There were three different HIP treatments, with details provided in Refs. [10,11]. HIPed and no HIP ingots were cut into $25 \times 25 \times 125$ mm bars that were then solution treated at 488 °C for 2 h, ramped and held at 510 °C for 2 h, ramped and held at 530 °C for 8 h and were subsequently quenched in still water at room temperature. Samples were naturally aged for 14 h and artificially aged at 185 °C for 5 to T71 condition. Tensile specimens of 12.8 mm diameter and 50.8 mm gage length and fatigue specimens of 8 mm diameter and 108 mm length were machined from the heat-treated bars. Tensile tests were conducted at room temperature following ASTM E8 standard. Ten fatigue tests for no HIP and 30 combined fatigue tests for the three HIP treatments were conducted at room temperature following ASTM E466. Fatigue specimens were tested at a maximum stress of 170 MPa, $R=0.1$ under load control using a sine waveform at a frequency of 60 Hz in laboratory air (room temperature, 20 °C, relative humidity, 70%). Tests were run to failure or stopped at 10^7 cycles.

Table 1
Chemical composition (wt%) of A206 ingots used in this study.

Si	Fe	Cu	Mn	Mg	Ti	Al
0.02	0.07	4.62	0.33	0.31	0.20	Rem.

3. Results and their reanalysis

3.1. Analysis of micrographs and fractographs

Fig. 1 shows the microstructure of as-cast ingots where many bifilms and much porosity are evident [11]. For the most part, the bifilms are associated with porosity and are located at dendritic solidification fronts in eutectic areas which are the last areas to solidify. In Fig. 2, the crack-like nature of bifilms can easily be observed with a variety of space existing between the two oxide layers that make up the bifilm [11]. The HIPed samples have essentially no measurable porosity. In addition, the HIPed bifilms appear more broken up and draped with copper rich eutectic particles.

Fig. 3 shows as-polished views of fractured bifilms under the fracture surfaces of HIPed specimens, with the direction of stress parallel to the page length [11]. The specimens with low properties had more and larger bifilm areas that appeared to be fractured (or separated).

Fractographs of no-HIP and HIPed tensile tested specimens taken via a scanning electron microscope are presented in Fig. 4 [11]. For the no-HIP sample with low elongation, much porosity and many bifilms and chunky spinel oxides covered dendrites on the fracture surface. Energy dispersive spectroscopy (EDS) revealed a relatively high amount of magnesium and oxygen associated with the oxides. All fracture surfaces examined for HIPed samples with low elongation showed a limited number of what appeared to be partially healed spinel oxides with reduced amounts of magnesium and oxygen. Many areas of unhealed bifilms were observed. Much of the fracture surface for the no-HIP specimen with high elongation and nearly the entire fracture surface for HIPed specimens with high elongation exhibited ductile fracture features free of pores. SEM analysis of fracture surfaces of fatigue specimens showed that all fatigue cracks for no-HIP specimens initiated at surface-connected porosity containing various amounts of alumina and spinel bifilms [10]. All fatigue cracks for HIPed specimens initiated at surface-connected or interior oxides, predominantly “old” oxides.

3.2. Weibull analysis

The average yield strength of no-HIP and HIPed specimens were 266 and 290 MPa, respectively. The tensile and fatigue results were analyzed by using the Weibull distribution [12]:

$$P = 1 - \exp\left[-\left(\frac{\sigma - \sigma_T}{\sigma_0}\right)^m\right] \tag{1}$$

where P is the probability of failure at a given stress (strain, fatigue life, etc.), σ, or lower. The threshold value, σ_T, is the value below which no specimen is expected to fail. The term, σ_0, is the scale parameter, and m is the shape parameter, alternatively referred to as the Weibull modulus. The elongation data (number of data, $n=46$) for various HIP treatments were combined and reanalyzed in the present study[1]. The Weibull probability plot of elongation for no-HIP ($n=33$) and HIPed specimens is presented in Fig. 5. Probability was assigned to each data point by using the following plotting position formula:

$$P = \frac{i - 0.5}{n} \tag{2}$$

where i is the rank in ascending order. Note that the data for no-HIP specimens show a linear trend, which indicates that the threshold is zero [13]. The HIPed specimens, however, have two different trends: (i) at low elongation values, the trend is a curve, rather than a line, which indicates a positive threshold [13], and (ii) at higher elongation values, there is a sudden change in the slope of the fitted curve, which indicates the presence of Weibull mixtures [13] which can be modeled as

$$P = p\left(1 - \exp\left(-\left(\frac{\sigma - \sigma_{T1}}{\sigma_{01}}\right)^{m1}\right)\right) + (1-p)\left(1 - \exp\left(-\left(\frac{\sigma - \sigma_{T2}}{\sigma_{02}}\right)^{m2}\right)\right) \tag{3}$$

where p is the fraction of the lower distribution and subscripts 1 and 2 refer to lower and upper distributions, respectively. The estimated parameters for the no-HIP and HIPed specimens are provided in Table 2.

Analysis of fracture surfaces of tensile specimens via scanning electron microscopy (SEM) showed [8] that the defects that led to premature failure in no-HIP specimens were “old” and “young” oxides and associated large pores. In HIPed castings, there were no pores, as can be expected. The “old” oxides were found to be resistant to healing and therefore cracks remained even after the pores around the old oxide bifilms were closed. The lower distribution in HIPed specimens is predominantly due to premature failure from “old” oxide bifilms. The upper distribution represents premature failure due to “young” oxide bifilms that form during pouring and filling of the current casting (as opposed to old oxides representing former damage). The young bifilms, unlike old bifilms, were partially healed during the HIP treatment. Therefore the upper distribution represents the case where an “old” oxide crack either does not exist in the casting or is parallel to the direction of loading. Hence the Weibull mixture model presented in Eq. (3) which is built on the assumption that “no competition” is applicable in this case. Therefore, the “old” oxides “win” all the time over partially-healed “young” oxides to lead to premature fracture in HIPed castings. Hence it can be concluded that for elongation to be improved significantly by HIP, the coarse, large “old” oxide films should not be present in the casting.

[1] Note that two datapoints from the “no HIP”, included in the original analysis were disregarded due to evidence of recording error.