Materials and Design 65 (2015) 473–481

Contents lists available at ScienceDirect

Materials and Design

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

Effects of surface quality and loading history on fatigue life of laser-machined poly(methyl methacrylate)

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ARTICLE INFO

Article history:
Received 17 June 2014
Accepted 6 September 2014
Available online 16 September 2014

Keywords:
Fatigue life
Poly(methyl methacrylate)
Surface quality
Multi-stage loading
Laser-machining

ABSTRACT

In this research the effects of surface quality and loading history on fatigue behavior of CO_2 laser-machined poly(methyl methacrylate) are investigated. It is found that polishing of laser-machined surfaces can enhance the tensile strength up to 5% while significantly elongating the fatigue life of specimens. Microscopic observations reveal that defects on lateral laser machined surface and heat affected zone lead to a reduction of fatigue life by a factor of ten compared to samples with polished lateral surfaces. In the second part of this research it is observed that the loading sequence has a definite effect on the remaining life of poly(methyl methacrylate). Finally the ability of several cumulative damage formulations for modeling the fatigue life in multi-stage loading is evaluated, out of which Manson–Halford and Otani–Song models outperformed the others.

1. Introduction

Polymers are widely used in a wide range of structural applications such as composite matrix and bio-compatible materials [1–6]. Poly(methyl methacrylate) (PMMA) is one of the biocompatible polymers used in industrial and medical applications. This polymer is known as an excellent candidate for design and fabrication of contact lenses, bone cements, denture's base materials etc. [1–4]. PMMA is a hard and stiff polymer with the highest surface hardness among all common thermoplastics [7]. Moreover, PMMA shows high scratch and weather resistance properties as well as tensile, flexural and impact strengths. The medical elements with PMMA base often operate in human body under cyclic loading for a long time. As an example, bone cement is subjected to repetitive loading in vivo [4]. In this regard, understanding the fatigue behavior of PMMA-based materials is crucial for design and manufacturing of medical products and devices [4,8,9]. However in previous studies, all aspects of fatigue behavior of PMMA have not been addressed.

In recent decades, laser machining has been employed to fabricate PMMA components due to the ability of multi-directional and support-free machining, automation and adaptive controlling [10–16]. Laser machining affects the surface quality of PMMA specimens [17] where laser and polymer material interact in a way that the evaporated polymer forms bubbles in the vicinity of cutting surfaces and result in a pronounced surface roughness [18]. It should be noted that the surface quality might affect the mechanical behavior of specimens [19,7]. Based on a defect tolerant approach [20], the fatigue life of a component can be greatly influenced by surface quality [20]. Effect of surface quality on the fatigue life of metallic materials was addressed in previous researches [21,22]. Surface modification e.g. polishing can increase the fatigue endurance of metallic components [22] even thou in some cases the irregular micropores created by laser texturing can increase the fatigue life [23]. In comparison with metals, effect of surface quality on fatigue life of polymers has not been addressed systematically and fewer researchers have investigated this issue [24–27]. Thus a part of this research is dedicated to study and compare the fatigue behaviors of polished and unpolished laser-machined samples of PMMA.

Besides surface quality, understanding the material response to loading history and developing quantitative models for predicting the fatigue life under multi-stage loading are important issues for design and fabrication of PMMA-made components. The loading history has a great influence on the damage processes and concomitant fatigue life of specimens [28]. During cyclic loading of inelastic materials some parts of strain energy is not recovered [29] but dissipated via accumulating damages. This damage accumulation is considered in different theoretical models to estimate the remaining life of structural components in multi-stage loading

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http://dx.doi.org/10.1016/j.matdes.2014.09.011
0261-3069/

[30,31]. The Palmgren–Miner rule is one of the simplest models proposed to evaluate the cumulative damage [30]. Other cumulative damage models have been developed for more precise modeling of the fatigue life of metals in multi-stage loading conditions [30–34]. Unfortunately to the best knowledge of the authors, none of the above mentioned researches is dedicated to investigate the damage accumulation in PMMA. The last part of this paper is devoted to investigate the fatigue life of PMMA, in the step loading condition, considering two increasing and decreasing regimes where quantitative models are evaluated to calculate the fatigue life of the test specimens.

2. Experimental detail

2.1. Material

All tensile and fatigue tests samples are made of commercial poly(methyl methacrylate) (PMMA) sheet of Evonik Degusa Company Plexiglas by laser machining.

2.2. Specimen preparation

To study compression–tension fatigue behavior of PMMA, special dog-bone specimens were machined with laser beam according to the dimensions presented in Fig. 1. The fatigue specimen dimensions were tailored similar to ASTM D695 guideline to prevent specimen from buckling during compression loading. Time of machining of each sample was 60 s. A 50 W CO_2 Laser with on-time of 10 ms and 100 Hz repetition was employed for machining the samples. Two groups of samples were prepared. First group was machined with CO_2 laser without any polishing, S0 samples and the 2nd group, S1 samples, was polished with sandpaper #1200 following with sandpaper #2000 parallel with the loading direction until all surface defects are eliminated and no machining effect was observed under 50× objective of an optical microscope. The summary of the preparation method is listed in Table 1.

Comparison between the surfaces of S0 and S1 samples, Fig. 2, reveals that negligible chill marks remain on the surface of samples after polishing. The values of arithmetic center line average, R_a, and mean middle peak to valley, R_z, were measured using a Taylsurf CCI non-contact surface profiler series 1200 with optical resolution of 0.4–0.6 μm whose the results are listed in Table 2.

Table 1
Sample preparation procedure.

Sample	Laser cut	Polish with sandpaper
S0	Y	N
S1	Y	Y

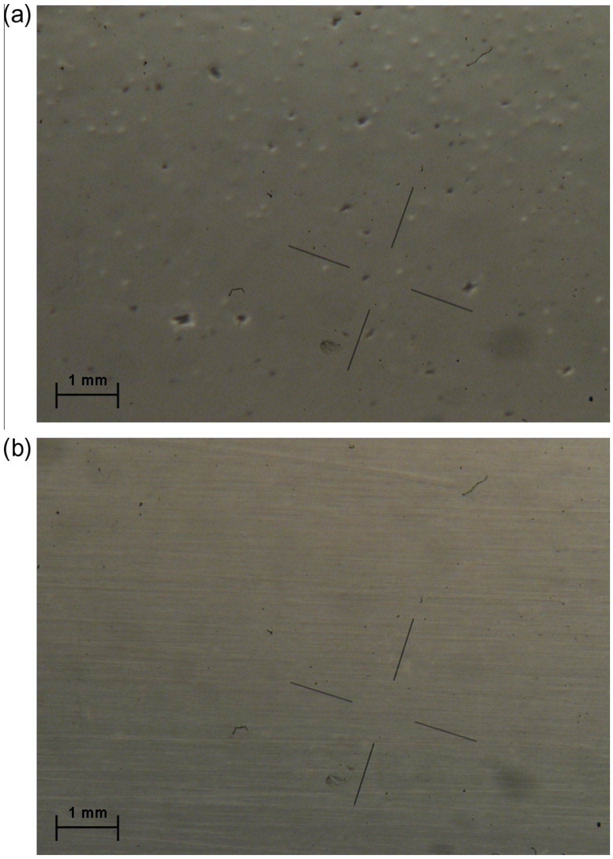

Fig. 2. (a) Laser-cut surface of the samples; dark points are chill marks and (b) surface of the samples after polishing.

Table 2
Roughness parameters of the PMMA samples.

	S0	S1
R_a (μm)	3.9	0.9
R_z (μm)	17	3.1

2.3. Tensile test

Tensile tests were conducted in ambient temperature, 23 °C, using an INSTRON 8502 machine. The specimens with the geometry according to ASTM: D638 guideline were loaded with the cross head rate of 5 mm/min.

2.4. Fatigue test

Fatigue tests were performed with stress ratio, R, of -1 under load control condition whose stress levels ranged from 0.2 to 0.85 of fracture stress. Fatigue tests were continued up to final fracture. In high frequency test, heat accumulates in the specimen to a degree that might even melt the polymer [35]. This heat accumulation changes the elastic modulus and this can be clearly observed in compression part of hysteresis loop, see Fig. 3.

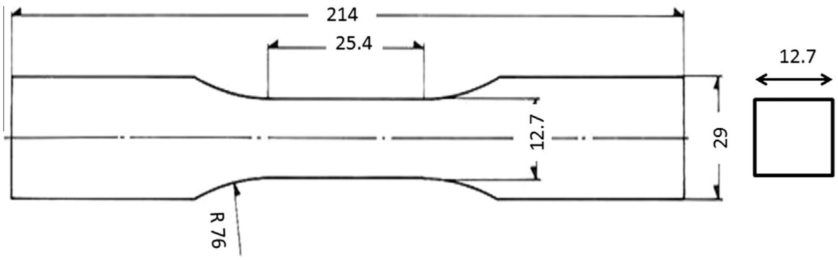

Fig. 1. Geometrical dimensions of fatigue test specimens. 12.7 × 12.7 × 25.4.