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Fabrication and high-temperature properties of Y-TZP ceramic helical springs by a gel-casting process

Mengmeng Zhuang[a,c], Mingchao Wang[a], Yingna Zhao[b], Bin Zheng[a], Anran Guo[a], Jiachen Liu[a,*]

[a]Tianjin University, 92 Weijin Road, Nankai District, Tianjin 300072, China
[b]Hebei United University, 46 Xinhua Road, Tangshan 063009, Hebei, China
[c]China Automotive Technology and Research Center, 68 East Xianfeng Road, Dongli District, Tianjin 300300, China

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Abstract

A rectangular cross-section ceramic helical spring of yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) was prepared by the gel-casting process. Both the compressive curves and comprehension rebound curves were tested at room temperature and high temperature. The results showed that springs obeyed Hooke's Law at room temperature, as the compression resilience ratio of the samples was nearly 100% under the condition of spring's security and no damping loss occurred during the process. Besides, mechanical failures of springs occurred under loads around 128 N with the deformation of 10%. With increasing test temperature the maximum load-carrying capacity of the spring decreased, while the maximum deformation increased. Besides, the load–compression curve showed a yield step when the test temperature was above 800 °C. At elastic stage of spring under high temperature, the compression resilience ratio was also nearly 100%; however, the anelastic effect took place and energy loss increased with the increase in test temperature.

Keywords: Y-TZP; Gel-casting; High temperature performance

1. Introduction

As one of the key construction components, helical springs are widely used in cushioning and damping devices due to their excellent properties such as high shock resistance, low energy loss and good elastic property [1]. Traditionally, springs are made of metal or alloy materials. Most commercially available alloys experience more and more severe creeps when the temperature is above 427 °C, and even the high-nickel alloys with good oxidative resistance are limited to 650 °C. However, with the development of hypersonic vehicles, the high-temperature-resistant and antioxidant springs are urgently needed in high temperature seal and damping installation [2,3]. Due to the poor behavior of metal springs at high temperature, it is risky to use them in high temperature environment. As is known, ceramics possess properties like good thermal and environmental stability, high hardness and good wear resistance, low density and coefficient of thermal expansion (CTE) [4]. Therefore, it is significant to fabricate a high-temperature-resistance ceramic helical spring providing appropriate property at high temperature in the air [5,6].

Helical ceramic springs were firstly manufactured from sintered vitreous-bonded alumina by R. H. Rudolph in 1961 [6]. Kaya made a zironia-toughened alumina (ZTA) spring from the extruded sol-derived pastes [7]. Barbieri prepared Al_2O_3 helical springs by a low-pressure injection molding [8,9]. Although there are so many methods to fabricate ceramic springs, few can be used in the industrial applications because it is difficult to achieve mass production [3]. In addition, due to

*Correspondence to: Key Lab of Advanced Ceramics and Machining Technology of Ministry of Education, School of Materials Science and Engineering of Tianjin University, 92 Weijin Road, Nankai District, Tianjin 300072, China. Tel.: +86 13902072240; fax: +86 022 27408244.
E-mail address: jcliutju@gmail.com (J. Liu).

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ceramics' brittle character and high hardness, it is difficult and expensive to manufacture springs from ceramics directly. What is more, even a very small defect can cause the failure of the ceramic spring component [10,11]. Gel-casting is a near-net-shape forming process, which has advantages over other conventional ceramic forming methods such as dry pressing, slip casting, tape casting and injection molding. The products of gel-casting have high green density, low shrinkage and defects [12,13]. Therefore, gel-casting is an attractive ceramic forming process for making high-quality and complex-shaped ceramic helical springs [14,15].

Al_2O_3 helical springs prepared by Barbieri had an axial deformation up to 10% at room temperature (RT) [8,9]. Hamilton used modeling equations which are suitable for metallic springs in an attempt to model the RT behaviors of MgO partially stabilized zirconia helical springs, and the results well obeyed Hooke's Law [2]. In addition, he expanded the analysis by using a more extensive model based on Hooke's Law. However, most references related to ceramic springs contained only limited data and almost all the ceramic springs' mechanical performances were tested at RT. The high-temperature property of ceramic springs has rarely been reported.

It is possible for ceramics such as Si_3N_4, SiC and Al_2O_3 to work at approximately 1000 °C. However, all of these three materials have their own deficiencies. Si_3N_4 and SiC have relatively poor oxidation resistance at high temperature. Although Al_2O_3 has good performance on oxidation resistance, its toughness is lower than Si_3N_4 and SiC [16]. As one of the good oxidation resistance, high toughness and high strength materials, yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) are widely used in oil exploration, engine production and other aspects of the life. In addition, when the temperature rises, the volume expansion of Y-TZP prevents the crack from expanding in order to achieve toughening results. Thereby, Y-TZP was chosen as the raw material to produce helical springs.

In this paper, rectangular cross-section ceramic helical springs were fabricated from Y-TZP by the way of gel-casting. The compression rebound curves of Y-TZP springs at different heat-treatment temperatures (from RT to 1100 °C) were tested and the energy loss under each cycle was also calculated. Besides, it was discussed in this work whether the relationship between compression load and displacement under room or high temperature obeyed Hooke's Law as well as the failure mechanism of ceramic springs under compression was also analyzed.

2. Experimental

2.1. Raw materials

Commercially available yttria-stabilized tetragonal zirconia polycrystals powder (d=300 nm; Fan Meiya Co., Ltd., Jiujiang, China) with density of 6.05 g/cm^3 were used as the raw material. Besides, the chemical composition of the powder was 94.8 wt% ZrO_2 and 5.16 wt% Y_2O_3.

Deionized water (Jiangtian Chemical Co., Ltd., Tianjin, China) was used as the shaping solvent in the gel casting process. A premix solution was prepared through adding the

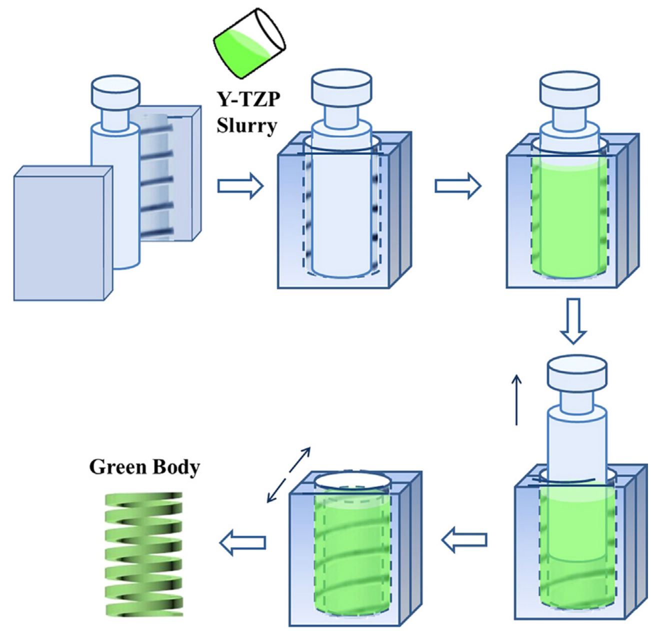

Fig. 1. Schematic diagram of the Y-TZP ceramic springs preparation process.

monomer (acrylamide, AM, $C_2H_3CONH_2$) and the cross linker (N, N-methylenebisacrylamide, MBAM, $(C_2H_3CONH)_2$-CH_2) into deionized water (DIW) based on the weight ratio of 10:1:50 (AM:MBAM:DIW). Ammonium persulfate (APS) and N, N, N′, N′-tetramethylethylenediamine (TEMED) was selected as the initiator and the catalyst, respectively, for cross-linking reaction. Citric acid was used as dispersant (0.6 ml per 100 ml slurry) to produce stable Y-TZP suspensions in deionized water. All chemicals used in this study were analytical (AR) grade.

2.2. Experimental procedure

2.2.1. The preparation of the spring

The Y-TZP ceramic springs were fabricated by the gel-casting process, as shown in Fig. 1. A slurry mixture including Y-TZP powder, premix solution, initiator, catalyst and citric acid solution was prepared by ball-milling for 4 h (ND7-2L ball grinding mill). The obtained slurry with 85 wt% solid loadings was stable and had good liquidity for casting. Then initiator solution and catalyst was added in the slurry followed by pouring it into polyethylene molds as shown in Fig. 1. A series of bulk specimens with the size of $45 \times 5 \times 5$ mm^3 were also prepared by the above method. After several minutes of AM's polymerization, high strong green bodies were removed from molds and dried at 50 °C for 12 h. The obtained samples were firstly heat treated at 600 °C for 0.5 h to decompose the organic phase and secondly heat treated at 1500 °C for 2 h (KSL1700X furnace) to complete the sintering process. After furnace cooling and being slightly polished, ceramic helical spring products and bulks were finally manufactured.

2.2.2. Testing and analysis

The crystalline phases of samples were identified by XRD (Cu Kα radiation, D/Max-2500 Rigaku, Japan) from 10° to 90° with