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Effect of non-metallic inclusions on the fatigue strength of helical spring wire

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ABSTRACT

This work aims to evaluate the effects of the presence of non-metallic inclusions in the early failure of a helical spring subjected to regular design loads during its operation. In order to do so and also to reach a better understanding of the reduction in fatigue strength, an analytical model was used. A two-dimensional (2D) Finite Element Method (FEM) analysis was developed to evaluate the residual stresses originated around an inclusion located near the material surface, by the application of a shot peening process. A three-dimensional (3D) FEM model was developed to study the stress concentration around the inclusion that appears under design loads. This study shows that the analytical model developed by Murakami (2002) [1] provides a valid insight on the fatigue strength reduction and that the FEM model may actually provide good qualitative and quantitative data that can help to obtain a better understanding of the process of early failures of spring wires with non-metallic inclusions.

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1. Introduction

The conventional theory regarding the phenomenon of fatigue in high efficiency steels features a well defined limit strength zone in high correlation with a specific number of cycles. This zone is identified by general acceptance as being above 10^7 cycles. Murakami [1] points out that in the *S–N* curve, the majority of the steels clearly show an angular bend at approximately 10^7 cycles. After this point, the fluctuating stress which goes below the stress corresponding to this number of cycles would not be a reason for the appearance of a crack and its propagation from the surface, causing failure. This concept was used for a long time as the basic idea for the design of mechanical components including helical springs.

Helical springs are used in, among other applications, combustion motor valves, and clutching or injection systems. They are typically subjected to cycling conditions that go beyond the limit condition of 10^7 cycles, and are called – Very High Cycle Fatigue – applications or VHCF. It can be observed that, when designing springs using the conventional theory of fatigue strength, failures continue happening after 10^7 cycles, according to Pyttel et al. [2]. Tests performed by Berger and Kaiser [3], show that the failure curve continues to drop with another inclination, even for a number of cycles higher than 10^7, which explains the failures in the region of VHCF. According to Bathias [4] and Sonsino [5], "a real fatigue limit can only be achieved in absence of microstructural inhomogeneity's or when there is no interference of a corrosive medium". This brings up the importance of using *S–N* curves that can predict the decrease in fatigue strength in VHCF conditions for the design of helical springs.

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Kaiser and Berger [6] recently made an important revision of this theory. In their work, they evaluated springs submitted to compression loads ($R > 1$) and manufactured from different material grades, according to DIN EN 10270-1–3 [7]. An initial evaluation was performed using HCF – High Cycle Fatigue – conditions, i.e. up to 10^7 cycles and they found out a level of fatigue strength for what they called "stroke stress" (=two times the amplitude stress) using different grades and diameters of wire. Also from the same work, and later published in other two different publications, Berger and Kaiser [3] and Pytel et al. [2] evaluated the fatigue strength of the Cr–Si-alloy, oil quenched and tempered, identified in the DIN EN 10270-2 [7] standard as VDSiCr, in VHCF up to 1.2×10^9 cycles conditions. In these studies, they used springs made with 2.0 mm diameter wires and treated with shot peening on its surface. The main conclusion of their work was that there is not an identifiable endurance limit for this type of material and that during tests performed in the VHCF cycling range, there was a reduction of about 25% in the fatigue strength for 1.2×10^9 cycles. In VHCF, instead of having the fractures starting from the material surface due to its defects, they started below the surface due to micro-defects and/or presence of inclusions in the matrix.

Complementing their previous work, Kaiser et al. [8] evaluated the VHCF behavior for three different spring wire materials, in two different wire diameters (1.6 and 3.0 mm), under compression fluctuating loads ($R > 1$). The materials analyzed this time were oil quenched and tempered SiCr and SiCrV valve spring steel wires and stainless steel wire, all treated using shot peening to increase surface fatigue strength. The tests were also conducted at up to 10^9 cycles, and the authors came to the conclusion that the *S–N* curves for springs made of SiCr and SiCrV alloyed spring steel wires are similar, while the *S–N* curves for springs made of stainless steel spring wires show a much steeper slope. They also found that springs made of 1.6 mm SiCr and SiCrV spring wires presented a reasonably expected number of failures due to fretting fatigue at the end of the coils, mainly due to the combination of the higher hardness and brittleness of this wire diameter and the shot peening applied on the springs. With this work, the authors concluded that different conditions between specimens made of spring material or springs manufactured with original wires and then shot peened can strongly influence the final component's strength at VHCF.

Akiniwa et al. [9] also performed a fatigue evaluation of oil-tempered SiCr steel wire used for valve springs (JIS G3561, SWOSC-V), under axial and torsional loading in the VHCF regime. The *S–N* curves obtained for tension and compression as well as torsion fatigue loading, could be approximated using power law functions, as it had been demonstrated in previous studies. They also found that the ratio of torsional fatigue strength to axial fatigue strength for the same number of cycles was 0.68, and almost constant up to the VHCF regime. Differently from previous studies, the failure started on the surface of the material, probably because the mentioned tests were performed with machined work pieces, polished with emery paper #800, and a surface layer of 50 μm was removed using electro-polishing, in order to eliminate residual stresses.

Pytel et al. [10] investigated the effect of a range of influences on fatigue behavior of helical compression springs at VHCF conditions. The work was conducted using three material grades: oil tempered and quenched SiCr and SiCrV spring steel wires, and stainless steel spring wires in two different diameters, and with the application of a single and a double shot peening surface treatment. As in previous studies, the authors concluded that there is no fatigue limit but a remarkable decrease in fatigue strength in the region of $10^7 < N < 1.5 \times 10^9$ in all the grades tested. An important conclusion is that a second shot peening treatment improved the fatigue strength of springs made of SiCr and SiCrV alloyed spring steel wire with a diameter of 1.6 mm and increased the percentage of subsurface failures. According to the authors, SEM analysis on the wire surface of the springs that suffered double shot peening showed a bit smoother and more uniform surfaces in comparison to the single shot peened springs.

In this article we are going to examine a case of early and unexpected spring failure that occurred at the HFC region around its 10^7 cycle's life submitted to a compression–tension load with $R = -0.79$. A model of the component for this case can be seen in Fig. 1, as well as its boundary conditions. The spring was manufactured with VDSiCr spring steel, using a wire diameter of 7.2 mm. The component was also subjected to a double shot peening treatment, which is going to be detailed

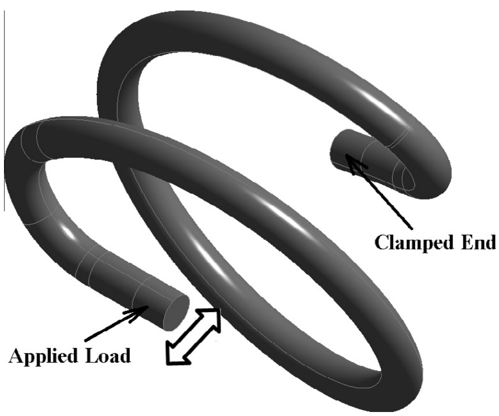

Fig. 1. Geometry and load applied on the helical spring of this study.

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