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The influence on gear surface properties using shot peening with a bimodal media size distribution

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ABSTRACT

New technologies developed for automotive engines also have highlighted the transmission torque capacity as restriction factor in the development of enhanced vehicle dynamics performance. Generally, the restriction is defined by the lifetime of the first speed gear. At the end of the gear manufacturing process, shot peening is used to induce compressive residual stresses and further increase fatigue life. This research verified the influence of introducing a bimodal media size distribution into the shot peening process. The proposal is supported by the independent effects of each media class. A higher compressive residual stress can be obtained from larger spheres. And the use of a lower diameter media class improves the surface homogeneity. The bimodal distribution was defined with a probabilistic approach over plasticity and contact stress theories. The experimental validation scope includes a topography analysis and residual stress profile measurements. The results showed mixtures combining up to an increase of 30.9% in the compressive residual stresses without jeopardising the surface quality. The collected data supported the expectation for improving the gear lifetime. It also represented the validation of a new peening process. An improvement in the product properties can be achieved in comparison to the parts produced using conventional shot peening; additionally, a lower process lead time is required in comparison to that for dual peening.

1. Introduction

Many of the newest technologies developed to improve internal combustion engines are aimed at increasing the output torque and power. Frequently, these advances are in contrast with the torque capacity of the transmission, which is the interface system. For manual transmissions in particular, the restriction is defined by the first speed driver gear lifetime. Its high transmission ratio causes it to be submitted to large contact and bending stresses.

Contact fatigue is one of the most registered failure modes, resulting from increasing input torque. Additionally, the removal of surface material close to the pitch diameter is the most common representation of contact fatigue, caused by fatigue crack propagation and commonly known as *pitting* or *spalling*. Ding and Rieger (2003) showed that the differences between pitting and spalling involve the failure dimension, the crack propagation mode, the crack origin, the tooth failure region and the collapse mechanism. This study has a strong focus on the interaction of failure with the residual stress profile, and therefore, it is focused on the failure depth dimension. Antoine and Besson (2002) and Aslantaş and Tasgeriren (2004) also stated that pitting is a more shallow failure. According to their studies, pitting never exceeds a depth of 20 μm, while spalling can reach up to 200 μm into the specimen surface.

The transmission gear manufacturing process is defined by machining, followed by heat treatment. At the end, a finishing process is typically applied to improve the surface properties. Among the available technologies, shot peening is an important example of a finishing process. Its concept has been explored, at least since Almen and Black (1963). The goal of shot peening is to induce a compressive residual stress layer in the material to increase the fatigue life.

The compressive layer is induced by plastic deformation, which is the result of the mechanical impact of small round hard particles, or simply "media", according to SAE (2001). The peening media is accelerated with a kinetic energy that is raised by machine propulsion. The resulting residual stress profile is deeply influenced by the processing and machine parameters. The media is an extremely important factor, including its dimension, hardness and geometry.

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As stated by Löhe et al. (2002), the fatigue limit is improved by increasing the peak intensity and the total compressive depth. Mitsubayashi et al. (2004) clearly showed the dependent relationship of peak depth with fatigue behaviour on failure mode. Their studies clearly demonstrated that the residual stress peak occurs in the depth at which the crack achieved the lowest propagation rate.

To increase the process efficiency, dual peening is a fairly well known solution. It consists of a shot peening process, performed in two steps. As defined by SAE (2001), a larger media is used in the first step to induce the maximum residual stress intended. In the second step, a smaller media is used to homogenise the residual stress profile across the tooth surface. Dual peening is not at all advantageous because it brings productivity losses. This process increases the gear manufacturing lead time, demanding specific and more expensive manufacturing protocol.

This scenario discloses an opportunity to an optimised process. The challenge is to combine the advantages of both processes: the improvement in the product properties produced by the use of dual peening; and the reduced process lead time of a conventional shot peening. The scope of this study is the investigation of the media size as the approach to this challenge.

2. Background

The shot peening process is typically controlled by saturation verification, coverage inspection, the *Almen* test and residual stress measurements. The profile of residual stress as a function of depth is a key outcome, but achieving the desired profile must be approached together with homogeneity along the surface. Studies carried out by Boyce et al. (2001) and Kobayashi and Hasegawa (1990) showed even tensile state regions around a single indentation created from a spherical bead impact. An irregular control of the coverage area could induce heterogeneous residual stress layers, preventing improvements in the fatigue properties.

The residual stress profile resulting from shot peening is deeply influenced by the processing parameters, including the exposure time, shot speed and media properties. The media dimension influence, as the approach investigated in this study, has been previously published in several works. Kritzler and Wübbenhorst (2002) and Kostilnik (1994) are some of the most referenced examples.

In these two references, increasing the media diameter was found to result in increases in the intensity and depth of the residual stress peak. Simulations performed by Shivpuri et al. (2009) and the experimental results of Guagliano and Vergani (2004) converged with the references. The explanation given was based on energy; that is, as the media diameter is increased, the shot kinetic energy increases as well. Similarly, as the energy during contact is increased, the plastically deformed region grows. Thus, the residual stress intensifies and grows deeper.

Not all published works on this topic support the results referenced above. Studies by Hong et al. (2008), Schiffner and Helling (1999) and Stranart (2000) concluded that only the peak depth is influenced by the bead or shot diameter. The divergence appeared over the peak intensity, but none of these works were experimentally verified.

Focused on the influence of media diameter with respect to fatigue life, Mahagaonkar et al. (2009) applied a DoE technique over several process parameters. The conclusion presented was that, when combined with increased shot pressure, higher shot diameters induce an improvement in the part lifetime. Bird and Saynor (1984) used only the media diameter as an investigation parameter. Their work experimentally demonstrated that higher diameters lead to higher peening intensities. The fatigue life results, however, did not show the same behaviour. The fatigue limit increased with enlarging media, from the S70 class through the intermediate media classes, with the results showing stabilisation. Beyond this point, the lifetime was decreased. In particular, S550 generated the worst lifetime results.

Ahmad and Crouch (2002) and Parizani et al. (2007) performed tests with dual peening. Harada et al. (2007) investigated a process called microshot peening, which utilises significantly reduced media sizes. All were able to conclude that these processes induced improved fatigue lifetimes due to the increased homogeneity of the surface residual stress. George et al. (2004) verified the influence of media diameter by using a mixture of S230 and S170 media classes. Their results showed that the S230 class presents a higher *Almen* intensity than the mixture, but no residual stress or fatigue results were shown. Additionally, the use of a mixture does not present a bimodal distribution, and the justifications for the creation of this specific combination of media classes are not given.

2.1. Objective and expectations

The literature review showed that increasing the shot diameter leads to improved fatigue life. However, this behaviour is not linear, and large media can induce poor fatigue properties. The heterogeneity of the residual stress at the surface when impacted by higher media classes is explained. In this content, dual peening is presented as a solution for increasing the residual stress intensity without jeopardising the surface homogeneity.

A shot diameter histogram with distinct modes also would lead to the intended distinct effects achieved by dual peening. The use of a larger class has the ability to increase the residual stress intensities. Other, smaller classes are employed to homogenise these stresses along the surface.

This study aims to verify the influence on the gear surface properties of applying two different media classes by one shot peening step. This mixture should yield a special characteristic, known as a bimodal distribution.

The objective can be evaluated through a combination of the residual stress and surface area roughness characteristics. It is expected to create a product with a bimodal distribution that can lead to a more compressive residual stress profile without jeopardising the surface homogeneity. These achievements, in conjunction with the failure mode characteristics, ideally could allow for the conclusion of a likely improvement in the gear fatigue life.

3. Materials and methods

The media class selection and its percentage of mass contribution were defined with a probabilistic approach. The analytical model employed was based on plasticity and contact stress theories. The experimental validation scope includes a topography analysis and residual stress profile measurements.

3.1. Mixture proposals simulation

An analytical model combining both Hertz and plasticity theories was applied, as proposed by Li et al. (1991). An outline of the mathematical model is shown in Fig. 1. More details can be found in the study published by Li et al. (1991).

Mixture proposals were raised for different mass contribution percentages. Calculations were performed for nine mixtures spaced at 10% interval of mass contribution. The contribution started at 90% of the smaller media class and 10% of the larger class, followed by intervals to the opposite respective ratio.

The need to work with a bimodal distribution induced a special procedure in order to consider the media diameter in the analytical model used as reference. A stochastic approach was applied, allowing the results to be analysed as a probability map. In this context, Monte Carlo and Molecular Dynamics appear as potential method alternatives. Comparison studies with both methods were