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Robust methodology to simulate real shot peening process using discrete-continuum coupling method

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A B S T R A C T

Shot peening is widely used in automotive and aeronautic industries to improve fatigue life of metallic components. Its beneficial effects are mainly due to the residual stress field caused by the plastic deformation of the near-surface region resulting from multiple shot impacts. It is therefore important to know the values of the induced residual stresses in order to predict the mechanical strength of the peened component, and to know how these stresses vary by changing the shot peening parameters. The problem is that experimental measurement of residual stress is costly and time-consuming, and generally involves semi-destructive techniques. These difficulties make assessment of compressive residual stresses in real (industrial) peened components very challenging. On the contrary, numerical simulation can provide an alternative way to deal with this task. Consequently, several shot peening models have been developed in the literature. Although these models were successfully applied to investigate important physical phenomena encountered in shot peening, their application to assess residual stresses resulting from a real shot peening test is still not within reach. Indeed, due to computation costs and the complexity of the process, they cannot be directly applied to simulate a complete shot peening experiment. Development of a robust methodology allowing these models to properly simulate such an experiment at minimal cost (*i.e.* using simplifying assumptions) is thus needed. The present paper aims to meet this need. First, a new discrete-continuum coupling model combining the strengths of the existing shot peening models was developed. To avoid expensive computation times, only major shot peening features are included in this model. Then, a comprehensive methodology explaining how this model can be applied to simulate a real shot peening experiment was proposed. To validate the developed model as well as the associated methodology, they were applied to simulate a real shot peening experiment from the literature. Relatively good results were obtained compared to experimental ones, with relatively little computation effort.

1. Introduction

To improve life expectancy, durability and operating performance of metallic components, different methods can be applied. Generally, these methods include use of expensive advanced materials having higher mechanical strength, modifying the operating conditions (environment, loading, *etc.*) or simply enhancing the near-surface properties by introducing compressive residual stresses (CRS) in this region. In addition to its effectiveness, the last method seems to be the least expensive, which explains the great scientific interest in it. Consequently, several surface treatment techniques have been developed in this context. An overview of these techniques can be found in Ref. [1]. One of them is shot peening (SP) which is widely used to improve fatigue life of metallic components in automotive and aerospace industries due to its economical cost and applicability to various targets. This process entails bombarding a surface of metallic component with small spherical shots at high velocities (20–100 m/s). Each shot acts as a tiny ball-peen hammer that compresses and stretches the component surface. After each impingement, an indentation surrounded by a plastic region is created. The near-surface plastic strain generated during shot peening leads to a residual stress profile through the thickness. The residual stress is compressive at the top surface and tensile underneath the surface of the component to ensure the mechanical equilibrium. The surface work hardening and the compressive residual stress induced by shot peening allow to hinder crack propagation, as cracks originate mostly from the surface. This can improve fatigue life and resistance to stress corrosion cracking within the peened component

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[2–4]. However, the beneficial effects of this process are conditional upon respecting several conditions. Indeed, numerous shot peening parameters can hugely influence the effectiveness of this process [5,6]. For example, over- or under-peening can result in adverse effects on fatigue strength. Selection of the most suitable and optimal parameters to achieve an expected degree of improvement is always a matter of question in the designer mind. Such a question has received a great deal of interest over the years and significant amount of research has been done in understanding such a process.

Several researchers have used the experimental way to study shot peening. Lieurade and Bignonnet [7] and Wohlfahrt [8] have studied the fundamental mechanisms of shot peening. Mainly two mechanisms are at the origin of CRS: Hertzian pressure due to normal impact forces and surface stretching (enlargement) due to tangential impact forces. The fatigue performance not only depends on the CRS at the top surface, but also on the gradient inside the material. Maeder et al. [9] have investigated the influence of the most important SP parameters on the peening-induced residual stress. Three categories of SP parameters can be distinguished: process parameters, *e.g.* Almen intensity and exposure time, component parameters, *e.g.* component material, and shot parameters, *e.g.* size , material, velocity and impact angle of shots. Kobayashi et al. [10] have studied the difference between static and dynamic indentation tests using single and multiple shots. Static indentation is quite different from dynamic one, probably due to high strain rate effects. In dynamic indentation, single shot leads to tensile stress at the indentation center, whereas compressive stress is found in static indentation. The compressive stress induced by shot peening (dynamic impacts) is due to superimposition of residual stresses generated by impacts performed around each other. For more details of the experimental works, the reader is referred to Ref. [11]. Despite its effectiveness, the experimental way suffers from several difficulties related to the cost of experiments.

To avoid experimental difficulties, other researchers have proposed to study analytically the CRS in the peening component. Al-Hassani [12,13] and Guagliano [14] have proposed an analytical relationship between the peening-induced arc height and the residual stress profile in thin components, using tensile force and bending moment internally generated to equilibrate the total peening-induced stress. Guechichi [15] has proposed simplified formulas to predict the maximal value and the depth of the CRS field, using Hertz contact and elastic-plastic theories [16]. These formulas were later improved by considering different constitutive laws for the target material [17] and by considering the effect of the tangential friction between the shot and the target [18]. Li et al. [19] have proposed a simplified analytical model to calculate the CRS field due to shot peening in semi-infinite target components. This model was improved by Shen et al. [20] to take into account more shot peening parameters, such as size and velocity of the shots and material of the target component. Recently, Miao et al. [21] have proposed a combined analytical model, including models of Li et al. [19], Shen et al. [20] and Guagliano [14], to investigate the influence of the shot peening parameters on the resulting Almen intensity and on the residual stress in an Almen strip. Several other analytical models can be found in the literature, of which an overview is provided in Ref. [11]. Compared to experiments, the analytical models are much less expensive. However, they are generally based on simplifying assumptions which can affect their effectiveness. Furthermore, obtaining analytical solution from these models is often very mathematically challenging, especially when complex structures are involved.

With the help of the increasing computer power, numerical simulation have become an effective method to investigate the shot peening process. Consequently, several numerical models have been proposed in the literature [14,22–25]. An extended review of these models will be given in Section 2. The first numerical models developed in the literature consider only one shot impacting a target surface. Although they are extremely simplistic, these models allowed a better understanding of several physical phenomena encountered in shot peening. To study the influence of multiple impacts on SP results, other researchers have proposed models with multiple shots having initial ordered configuration. More recently, these models have been improved by considering randomly generated shots. Further improvements have proposed more complex SP models to take into account more complex mechanisms, such as interaction between shots, fluctuation of shot velocities and impact angles, shots deformation, thermal behavior of shots and target component, *etc.* [24,26,27]. The problem with application of complex SP models is that the computation time is an increasing function of the complexity of the involved SP phenomena. For instance, taking into account shot–shot interactions results in a computation time proportional to N^N, where N is the number of shots, which is much larger than that obtained when ignoring such interactions (the associated computation time is simply proportional to N). Therefore, although complex SP models generally guarantee a more efficient representativeness of a real SP process, their application to predict residual stresses resulting from a real SP experiment remains very challenging. Simulation of a complete SP test using such models can lead to unaffordable computation times. The challenge here is how to properly simulate a real SP experiment while keeping acceptable computation time. In other words, is it possible to correctly assess important results from a real SP test using a simplified numerical model that includes only major SP phenomena? The present paper aims to tackle this challenge. Based on the different (experimental, analytical and numerical) works on shot peening, this paper proposes an effective approach to properly predict the peening-induced residual stresses in a real shot peeing test with minimal computation effort. This approach consists of two parts:

- development of a simplified shot peening model based on simplifying assumptions to avoid large computation costs (only major SP mechanisms must be taken into account in this model). It should be noted that this model is similar to those proposed in the literature. And then,
- development of a robust and comprehensive methodology explaining how this simplified model can predict peening-induced residual stresses in a real (industrial) shot peening experiment.

As shown in the literature [25,28], for given shot type and impingement angle, the Almen intensity and exposure time are major indicators that ensure the effectiveness and repeatability of a given SP experiment. In other words, for given shot type and impingement angle, the SP results depend almost solely on these parameters (Almen intensity and the exposure time), and not on how individual shots impact the target component [25,28]. Using this finding, the key idea of the proposed methodology is then to satisfy the same repeatability conditions (Almen intensity and the exposure time) between the considered experiment and the associated simplified model. As will be explained later, it is not necessary to take into account all the complex and time-consuming SP mechanisms to correctly model a real SP experiment. The effects of such mechanisms can be considered indirectly by application of the proposed methodology which represents the major novelty of the present paper.

Following this introduction, this paper is divided into five sections. Section 2 gives an overview of the different classes of the SP numerical models developed in the literature. Based on this