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Influence of ball burnishing on residual stress profile of a 15-5PH stainless steel

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ABSTRACT

Ball-burnishing is a superfinishing process commonly applied to improve the surface integrity (surface roughness, residual stress, microstructure, hardness) of a mechanical component. This paper focuses on the influence of ball-burnishing on residual stress profile of a 15-5PH martensitic stainless steel. After a preparation of the surfaces by turning, various burnishing parameters were investigated to understand their influence on the residual stress profiles in axial and circumferential directions. It is highlighted that burnishing induces an intense and deep compressive layer. Among the ball-burnishing process parameters, the normal force is the most sensitive ones to modify the thickness of the affected layer and the peak of compression in the sub-surface, whereas the speed, the feed and the number of passes have a limited influence on the residual stress profiles.

Introduction

During machining and finishing processes, surface and sub-surface support intensive thermomechanical loadings inducing modifications of surface characteristics such as roughness, microstructure, residual stress and hardness (Fig. 1). These parameters are commonly included in the terminology "surface integrity" introduced by Griffiths [1]. Later this definition has been improved by Rech et al. [2], including the concept of reliability and service performance. A recent state of the art has been proposed by Brinksmeier et al. [3].

Several scientific works, such as Novovic et al. [4] and Sasahara [5], report that surface treatments, inducing a very low surface roughness associated with deep compression residual stress, have a beneficial influence on the fatigue life and corrosion resistance compared to the virgin material. Mechanical surface treatments, especially burnishing [6,7], are very good techniques to obtain such surface integrity characteristics and some authors have studied the impact on surface roughness, residual stress and on the microstructure on various materials. Ball-burnishing or roller-burnishing consists of rolling a hard ball or a cylinder on a surface, that plastically deforms the peak of roughness and moves the material to the "valleys" of the roughness profile (Fig. 2).

Among the 4 key criteria of surface integrity (surface roughness, residual stress, microstructure, hardness), almost all of the papers dealing with burnishing present results on the influence of burnishing on surface roughness. For instance, Loh et al. [8] provided a literature survey on this topic for cylindrical parts, whereas more recent works, such as Lopez de Lacalle et al. [9], have explored the burnishing process for complex parts on milling machines.

Regarding the evolution of microstructure, the number of concerned papers are much more limited. For example, Altenberger [10] reports that the microstructure produced by deep rolling hardly depends on the process parameters as well as the material itself. For body center cubic materials, such as AISI 1045, a microstructure layer resembling dislocation cell structures rather than nanocrystalline grains with high angle boundaries was observed. Pu et al. [7] has observed a severe decrease of grain size for a AZ31B magnesium alloy, as well as Grzesik et al. [11] for a 41Cr4 steel. The mechanism of dynamic recrystallization has been introduced by Pu et al. [6] to explain this sub-surface microstructure. Most of these investigations were concerned with ductile materials such as aluminum [12], magnesium [6] or ferritic-perlitic steels [7,13,14] whereas a limited number of papers deal with the burnishing of hard martensitic steels [15–17] that are commonly used to produce shafts for mechanical systems requiring a high level of fatigue resistance.

Regarding the influence of burnishing on residual stresses, all the papers confirm the generation of compressive residual stresses. Unfortunately, many researches have limited their investigations

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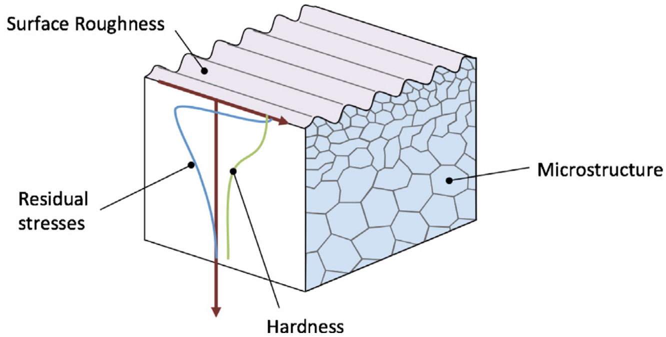

Fig. 1. Illustration of surface integrity parameters.

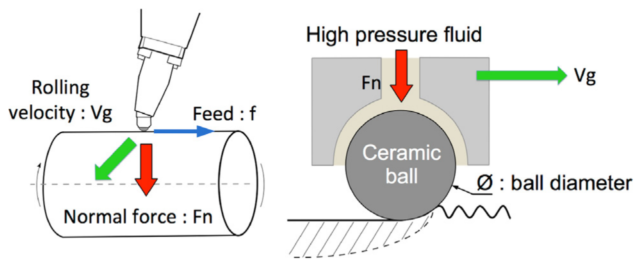

Fig. 2. Principle of the ball-burnishing process.

to the characterization of residual stresses on the surface [6,14,18]. This is not sufficient since cracks propagation strongly depends on the residual stress state in the subsurface. Some papers have investigated residual stress profiles. They have highlighted that the compressive layer has a depth of several tenth of millimeters. Unfortunately most of the papers have only characterized the effect of burnishing for a single set of process parameters [7,17]. It is only possible to report the work of Mhaede et al. [12] and El-Khabeery et al. [19] (aluminum alloy) and Rodriguez et al. (ferritic-perlitic steel) [13] and Zhang et al. (17-4PH martensitic steel) [15] that have investigated the influence of the normal force applied on the ball. They report that a higher normal force increases the depth of the affected layer. As a consequence, it is possible to state a great lack of experimental characterization on the influence of other burnishing parameters such as feed f, Number of passes N_b, Velocity V_g (Fig. 2) on residual stress profiles.

So this study aims at characterizing the surface integrity induced by ball-burnishing on a shaft made of a 15-5PH martensitic stainless steel and to investigate more in detail the influence of several ball-burnishing parameters (velocity V_g, feed f, number of passes N_b, normal force F_n) on residual stress profile in both directions (axial and circumferential).

Preliminary analysis of the reference surface integrity

Workmaterial

The workmaterial used is a 15-5PH martensitic stainless steel. Its composition is reported in Table 1. Bars have been heat treated in the H1025 state (quenched from 1020 to 1050 °C followed by annealing for 4 h at 550 °C and air cooling). Its Brinell hardness is around HB350 and the average grain size is around 30 to 40 μm. This grade is commonly used for power transmission in aeronautical applications.

Experimental set-up

The samples were first prepared by turning a cylinder (∅ 150 mm) as shown in Fig. 3a. The cutting conditions were selected based on the recommendations of our industrial partner.

The CNC lathe was also equipped with a ball-burnishing ECOROLL system consisting of a high-pressure supply pump plugged into a tool with a SiN ceramic ball (Fig. 3b). This set-up enables to modify on the one hand the normal force (F_n) by modifying the hydraulic pressure, and on the other hand the burnishing speed (V_g), the feed per revolution (f), the number of passes (N_b) by means of the CNC interface. The normal force was controlled with a dynamometer at the interface between the burnishing tool holder and the turret of the lathe. The burnishing conditions were selected based on the recommendations of the ball-burnishing manufacturer.

Characterization of surface integrity

Before launching the design of experiments, some samples obtained by turning and turning + burnishing with reference conditions (Fig. 3a and b) have been analyzed in terms of surface integrity (surface roughness, hardness, residual stress, microstructure).

Surface roughness

Fig. 3 presents the surface roughness profiles and parameters. It confirms the capacity of burnishing to improve significantly the surface roughness as reported by Loh et al. [8]. Especially the surface roughness profile obtained after turning + burnishing (Fig. 3d) is in agreement with a typical profile described by Loh et al. [8]. Thus it confirms that the reference burnishing conditions are appropriate with regard to the initial surface roughness and the workmaterial properties.

Hardness

Fig. 4 presents the evolution of the microhardness $Hv_{0.01}$. The bulk hardness is around 400 $Hv_{0.01}$. The turning process has induced a workhardening in a thin layer of 0.1 mm, whereas burnishing has increased the thickness of this harder layer around 0.3 mm. This trend is confirmed by several works [12,13].

Microstructure

Fig. 5 presents the microstructure in the affected layer after turning and after turning + burnishing. The thickness of the altered microstructure is limited (10 to 15 μm). Two zones can be clearly distinguished. In the first external layer, the EBSD analyses (Fig. 5c and d) reveal a finely recrystallized layer on the surface with a thickness around 2 μm. Below a largely deformed layer is present with a thickness between 7 and 10 μm. Then the bulk material is observable with the original grain shape.

Mondelin et al. [20] have made similar observations for the same 15-5PH steel by after turning. They report that this grain refinement corresponds to a dynamic recrystallization phenomena induced by the severe thermo-mechanical load generated by the

Table 1
Chemical composition of 15-5PH in wt%.

C	Mn	Si	Cr	Ni	Cu	Nb	S	P	Fe
0.07 Max.	1.0 Max.	1.0 Max.	14 to 15.5	3.5 5.5	2.5 to 4.5	0.15 to 0.45	0.03 Max.	0.04 Max.	Bal.