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# Experimental and numerical study of tooth finishing processes contribution to gear noise

S. Jolivet [a,*], S. Mezghani [a], J. Isselin [a], M. El Mansori [b]

[a] Arts and Métiers ParisTech. Mechanics, Surfaces and Materials Processing (MSMP), Rue Saint Dominique, BP 508, 51006 Châlons-en-Champagne Cedex, France
[b] Arts and Métiers ParisTech. Mechanics, Surfaces and Materials Processing (MSMP), 2 Cours des Arts et Métiers, 13617 Aix-en-Provence, France

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ABSTRACT

The contribution of gear tooth flank surface micro-finish on gear noise has not yet been taken into consideration. This paper is devoted to study the simultaneous effect of tooth roughness and lubricant viscosity on automotive gear vibrations. The vibrations performances were evaluated on an instrumented test rig under both dry and wet conditions. A non-destructive replication technique coupled to 3D optical measures was used to acquire the flanks topographies, which were characterized using multiscale decomposition. A three-dimensional finite element simulation of a helical gear was performed to assess the micro-scales impact on gear noise. Numerical representative surfaces morphologies were introduced into the simulation and compared through the transmission error calculation. Results have shown gear noise dependence on tooth finishing processes.



## 1. Introduction

The development of electric motorizations has increased the need for high quality gears in the automotive powertrain transmissions, as the combustion does not cover its noise anymore. It is known that gear meshing produces vibrations due to load variations on the teeth. Indeed, this uneven load generates excitations which are then transmitted to the environment and produce noise. Nevertheless, manufacturing and assembly defects such as profile [1,2], division [3–5] and eccentricity errors [6,7] amplify this inherent behavior by enhancing the existing excitations. To counteract this, teeth corrections such as crowning are put in place. The industrial manufacturing of gear tooth of a powertrain transmission for an automotive application involves an interrupted multistage process to meet its mechanical contact functionalities. It is a succession of several stages. First, the teeth are cut using a continuous hobbing operation. The gears are then shaved before carbonitriding. Shaving is a machining process in which the tool"s cutting edges (Fig. 1a) come scraping the tooth flanks during the meshing with the piece. It removes the fine particles under high pressure [8]. Then, carbonitriding allows the hardening of the surface, thus effectively reducing wear. Finally, the gear surfaces are shot-peened. Manufacturing errors due to these operations can then be reduced using a finishing operation after shot-peening such as power honing or grinding. Both of these are abrasive processes which use the meshing mechanics to machine the flanks. The power honing process (Fig. 1b), uses an internal gear with shafts that are not parallel to generate an increased lateral friction on the flanks and thus correct tooth surface irregularities [9]. Due to this, the load is important but balanced along the width of the teeth; it leaves high residual compressive stress [10]. Grinding (Fig. 1c) is very often used as a worming gear in order to generate friction between the abrasive surface and the workpiece. It is a process which has high cutting speed and thus induces high temperatures [11], which can lead to "grinding burns" on the flanks. The whole multi-step process produces structured surfaces which need to be characterized on the entire wavelength band.

In the automotive industry, vibratory tests are performed to select the adequate gear finishing process. However, they can quickly become time consuming and costly. Thus researchers have turned to simulation and modeling in order to overcome these limits. Nevertheless, these models take into account only geometrical deviations at the macro scale as it is required in manufacturing tooth specifications. They do not consider the finishing process and its micro-scale signature. Studies by Åkerblom [13,14] have focused on this effect without giving significant global conclusions but they showed that a higher roughness tends to increase gear noise by 1 or 2 dB. Most developed models calculate the gear transmission error, defined by Harris [15] and Welbourn [16] as the deviation between the theoretical angular position of the driven gear and its actual position. It has been shown to be the main cause of gear noise [17–19]. However, the multi-step manufacturing process can introduce micro-geometry deviations on

* Corresponding author.

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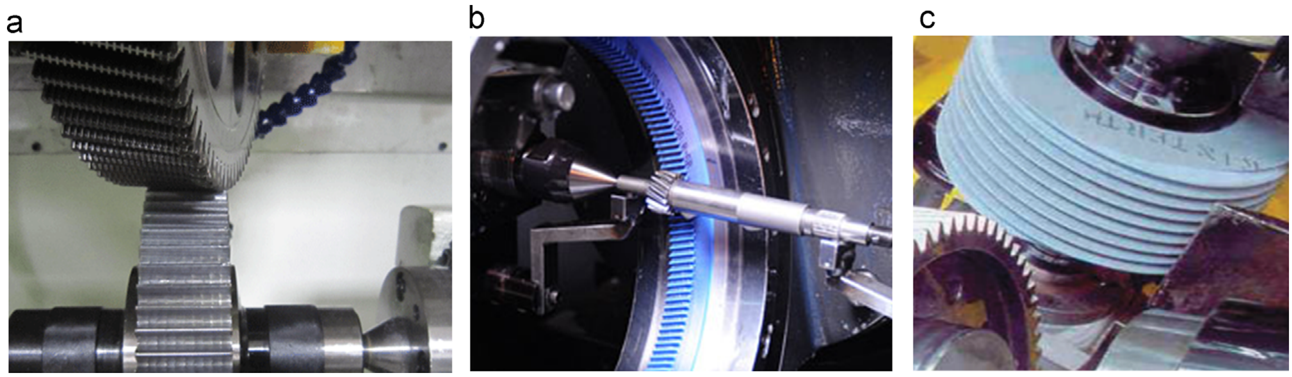


**Fig. 1.** Tooth flank finishing processes: (a) shaving process, (b) power honing with internal meshing and (c) grinding with worm meshing [12].

the flanks which can alter the meshing contact and influence gear noise [20].

In this paper, experimental and numerical studies were developed to study the influence of tooth finishing process on gear noise under dry and wet conditions. Three configurations are considered: not finished, finished by power honing and finished by grinding. The vibratory response of each gear as well as the topographic teeth surface modification have been used as a signature of the considered finishing process before, during and after the meshing tests. Furthermore, a finite element model of a helical gear computing transmission error has been developed. Then the relationship between the surface irregularities, the lubrication and the generated vibrations were analyzed in a wide range of wavelength from roughness to waviness.

## 2. Multiscale signature of each gear manufacturing step

In order to characterize the evolution of three-dimensional texture on the flank surfaces at different instants of the vibratory test, a nondestructive technique was used. Replicates of the primary shaft teeth were made with a silicone-based resin (Struers, Repliset F1) which were then measured at the primitive diameter with a white-light interferometer (WYKO 3300 NT –WLI), sampled at $515 \times 515$ points with a 3.88 μm step in both x and y directions. The form error component was removed from the acquired 3D data using least squared approximation method based on a cubic spline function.

Fig. 2 presents typical tooth surface morphology after each manufacturing steps. It is interesting to note that facets appear on the flanks after hobbing (Fig. 2a). The next step, the shaving operation, introduces oriented grooves on the surface (Fig. 2b). The carbonitriding does not significantly change the surface morphology (Fig. 2c). This figure also shows that surface topography (Fig. 2d) is very rough without the finishing step as compared to the finished surfaces. The power honing generates surfaces with curved grooves (Fig. 2e) while the grinding generates ones oriented in the helix direction (Fig. 2f). These are due to the significantly different process kinematics.

Fig. 3 gives the ISO 25178 standard parameters for each step. The arithmetic average roughness (Sa) is decreasing during the overall manufacturing processing. The roughness is very close between the two finishing processes, grinding and power honing; it is reinforced by their overlapping standard deviations. Three functional parameters from the bearing curve were considered for tooth surface characterization. The core roughness depth (Sk) is a measure of the surface with the predominant peaks and valleys removed. The Reduced Valley Depth (Svk) is a measure of the valley depth below the core roughness while the Reduced Peak Height (Spk) is a measure of the peak height above the core roughness. In the same manner as the (Sa) parameter, they tend to decrease as manufacturing advances. They also indicate that grinded surfaces tend to have higher functional peaks and less deep valleys. However the differences are not significant.

As the flanks were generated in several steps, the surfaces irregularities occur on large wavelength band. Then, multi-scale analysis based on the continuous wavelet transform was used to identify the relationship between surface irregularities and the functional finish product behavior [21–23]. Then, the surfaces were decomposed in the profile direction of the teeth, using Morlet wavelet function. The multiscale roughness spectra, called SMa, were then calculated [24,25]. It represents the arithmetic average roughness computed at each scale of the surface, and thus at each wavelength. From there, the Multiscale Process Signature (MPS) can be computed with the relative difference between the initial surface SMa and the final one:

$$MPS = \frac{SMa_{final} - SMa_{initial}}{SMa_{final}} \quad (1)$$

Fig. 4 shows the process signature of each manufacturing step, which is the relative difference of the SMa before and after the considered processing step. It demonstrates clearly that the shaving process introduces a high roughness on the facets made on the flanks by the hobbing tool (Fig. 2a). Indeed, while a representative surface after hobbing is very rough, the roughness inside these facets is very low. The carbonitriding operation dilates the surface and offers a small but significant increase of the amplitude in the waviness scales, superior to 0.2 mm. After that, the craters left by the shot peening operation largely increase the amplitude in the roughness scales, while leaving the waviness ones intact. In the end, the hard finishing operations correct the irregularities of the preceding steps at all scales. Furthermore, it can be noted that there is a difference between the two finishing processes: the grinding operation leaves higher waviness amplitudes on the flanks than the power honing step and reversely in the roughness scales. In the end, the finishing operation erases the irregularities left by the preceding steps on all scales.

## 3. Experimental vibratory tests on single stage gears

An instrumented low-powered vibratory testing rig for a single-stage gear was developed in order to test the gears, as shown in Fig. 5 [12]. The primary shaft is driven by a 2.4 kW asynchronous motor while a resisting load is applied by a 2.1 kW DC machine linked to a 4 kW rheostat. Both machines are assembled on silent blocs. Flexible couplings make the liaison with the electric machines to reduce the vibration transmitted to the gear.