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Particle swarm optimization for achieving the minimum profile error in honing process

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ABSTRACT

Gears are among the most important mechanical components of the modern industry. The topography of the gears' tooth flank has an intricate and complex form and requires great finishing and quality. Commonly, traditional grinding processes are applied to finishing gear profile. However, the use of honing process has grown in recent years to provide the best finishing in industrial products. In this study, the honing process was improved applying a particle swarm optimization. Pinions of steering systems were used as work pieces to testify the optimization technique. The input parameters were the spindle speed, feed rate in *X* direction, feed rate in *Z* direction, oscillation time, and spark out time. The experimental measures were compared with simulation tests using the responses total profile deviation (f_α), total helix deviation (f_β), and total cumulative pitch deviation (f_p). The results showed that profile error was minimized, and the quality was improved based a set of strategies that were held simultaneously in the input parameters.

1. Introduction

Gears are among the most important and complex mechanical components of the modern industry. Gears are used mainly in gearbox, reduction gear, and steering systems. The variety and multitude of the application of gears in mechanical components require great finishing and quality [1]. Based on this, the manufacturing processes to produce gears are constantly studied aiming to improve the quality and reduction the time and costs of production.

The topography of the gears' tooth flank has an intricate and complex form. Thus, the perfect gearing depends on the lowest surface roughness and the correction of the tooth profile by abrasive processes. The forging process was widely used to produce gears at the first stages of the manufacturing. The second stages include the milling, turning, and drilling with well-defined cutting edges [2]. Each manufacturing processes previously mentioned induce distortions that necessitate of corrections in the finishing of the wheel-body and the tooth flanks [3]. According to Karpuschewski et al. [4] the exact corrections such as flank changes and reduction of form errors have to be achieved with the most suitable manufacturing processes.

In addition, the manufacturing process should provide form errors correction and low surface roughness. The manufacturing sequence of the gears includes the hardening, rough, and finishing, which results in variation of the surface topography. The abrasive processes, such as grinding and honing, are applied in the manufacturing of gears due to the requirements of high hardness and low surface roughness of the gears. The use of the abrasive processes is important because according to Bergseth et al. [5], rough surfaces generate high local pressures and significantly decrease the real contact area compared to a smooth surface. Therefore, only abrasive processes have the ability of machining hardened materials producing a high-quality surface.

Abrasive processes can be distinguished by their kinematics and geometry, such as, flat grinding, cylindrical grinding, and centerless grinding. Each grinding process has specific configurations that define if they are relatively straightforward or very complex. The control over the input parameters for these processes with a general lack of understanding of the fundamentals can reduce the grinding applications successful. Moreover, all abrasive processes use high-speed cutting and a great quantity of cooling lubricants.

According to Brinksmeier and Giwerzew [6] several researchers have been directed toward the use of dry grinding or at least minimum quantity lubrication (MQL). High finish quality and accuracies can be reached by grinding, and a good finishing of hard materials is possible. However, grinding processes such as hard gear shaping and skive hobbing generate maximum gearing quality of

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approximately DIN6, while the honing process produces gearing quality of DIN2 [7]. The development of gear honing was applied in the 1970s to remove damages on hardened tooth flanks [8].

The great advantage of the honing is the adjustment of gearing failures and the favorable surface structure in height and width direction of the tooth flank [4]. The honing process is more complex than traditional grinding processes. Generally, the machine tools have nine degree of freedom and allow the manufacturing of several tooth profiles. Direct honing, single honing, and multi honing are some variations in the process. Direct honing corresponds to a three stage machining process. First the teeth are cut, then there is the heat treatment step and, lastly, there is the direct honing of the gear's teeth. Single honing and multi honing are variations of the honing process. In single honing a hard shaving is carried out after the heat treatment and before the traditional honing and in multi-honing a grinding process is performed after the heat treatment and before the honing process. The term multi-honing is applied because two abrasive processes, grinding and honing, are used in sequence to finish the gears. However, each process can be split into roughing and finishing steps. In some case, the use of simultaneous machining of two work pieces is possible [8].

This situation occurs because is available the presence of two work piece spindles for fast automatic change. Furthermore, the honing process shows some limitations linked to work piece dimensions due to machine tool size, but in opposite situation, there is no limitation for technological reasons [9]. The control over the input parameters for the honing process is as complex as the grinding processes. Axial and radial feed rate, spark out, cutting speed, abrasive grit, and inclination of crossed axis angle are some parameters used during the setup of the honing machine tools for honing. Based on this, optimization of the honing process is more difficult than other machining processes.

Marzenell and Tönshoff [10] affirm that the honing process has an established tooth flank that needs grinding with kinematics and tool that usually have a gear shape. Thus, we can consider that optimization of machining processes applying metaheuristic is a new tendency. Metaheuristic is a procedure designed to find a good solution to a difficult optimization problem. Popular metaheuristic methods for combinatorial problems include simulated annealing by Kirkpatrick et al. [11] genetic algorithms by Holland et al. [33] scatter and search by Glover [12].

Metaheuristic methods can be used to minimize surface roughness, cutting power, and chatter in machining processes and also defines the exact cutting speed determining the best input parameters in machining processes. Yusup et al. [13] give an overview of particle swarm optimization techniques to optimize machining process parameters of both traditional and modern machining processes from 2007 to 2011. The technique requires that empirical data is used to predict the optimal machining parameters for effective machining process. However, metaheuristic methods can be applied together with statistic techniques such as response surface methodology (RSM) or Taguchi method [14].

Grinding processes provides low surface roughness and form errors. However, the traditional techniques to define exactly the input parameters are not efficient enough to improve the quality in processes. Mohanasundararaju et al. [15] employed two techniques namely nonlinear programming and genetic algorithm to optimize the process parameters of grinding machining. The authors used the Box–Behenken design matrixes with six central points. Moreover, the RSM technique was used to develop a second-order mathematical model. According to the authors, the process parameters such as wheel and cutting speed, traverse speed, feed rate, and dress depth were optimized generating a high-quality considering the surface finish and dimensional accuracy.

Kor et al. [16] implemented a new particle swarm optimization method to determine the optimum process parameters for a minimum wear rate of a high chromium alloy during the grinding process. The PSO technique indicated that the optimum liner wear rate was within the lower and upper ranges used for all variables. Pawar et al. [17] developed a non-traditional optimization technique based on a PSO algorithm to find the optimal combination of process parameters in the grinding process. According to the authors, production cost, production rate, and surface finishing were predicted considering the thermal damage, wheel wear, and machine tool stiffness.

The swarm particle algorithm can be used to optimize not only grinding processes, but also other manufacturing process such as turning [18], milling [19], boring [20], and welding [21]. Raja and Baskar [22] applied a swarm intelligence algorithm to determine optimal machining conditions in a milled surface. The experimental results showed the effectiveness of PSO in predicting surface roughness. Moreover, the proposed technique reduced the time and cost of trial and error experiments in actual machining environments for the prediction of surface roughness.

Thus, this study proposed estimation equations for determining optimal machining conditions through the PSO algorithm technique as the basis of complete analysis of variance and experimental tests. The honing process has become a permanent part of the worldwide production process of high-output gear drives. Honing can be considered as an additional process, which is usually carried out after grinding. In this paper the Direct Honing of gears was developed and optimized. The honing procedures were performed directly on the hardened milled work piece.

The honing process has a number of input parameters to define the exact setup. These input parameters are interrelated and a change in an input parameter will have a direct influence on another parameter. Based on this, a PSO algorithm technique was used to define the optimal setting with simultaneous variation of all input parameters, minimizing setup time and optimizing the response parameters. In addition, the work was focused on the analysis on the changes of tooth profile, evolvent profile error considering a specific pre-defined model. Due to the complex setup of honing as well as traditional grinding processes, in this study, was found the exact point for each input parameter providing the optimization of honing process and improve its quality, mainly of the tooth profile.

2. Modeling process with response surface methodology

Response surface method is a set of mathematical and statistical models that are used to perform an analysis of the effects of independent variables on the response variables. In addition, a response surface analysis considers an adjusted surface. If the surface has an adequate adjust, then it will be approximately equivalent to the analysis of the actual process. The modeled response surface by a linear function of the independent variables, and the relationship between Y and the predictor variables can be expressed according to an expanded Taylor series with an approach function that will be a first-order model:

$$y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k + \varepsilon \qquad (1)$$

If there is curvature in the system, then the adjusted function corresponds to a polynomial of higher order, as the second-order model written below:

$$y = \beta_0 + \sum_{i=1}^{K} \beta_i x_i + \sum_{i=1}^{K} \beta_{ii} x_i^2 + \sum_{i<j}^{K} \sum \beta_{ij} x_i x_j + \varepsilon \qquad (2)$$

To estimate the coefficient (β) in the polynomials, the least squares method in matrix form was employed, which corresponds