Title:
Numerical and Semi-analytical Simulation and Process Optimization of Face-hobbing of Bevel Gears Considering Cutting Forces and Tool Wear

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Introduction:

Rule-of-thumb based design for cutting tools and machining setting selection in face-hobbing of bevel gears cause cutting tool failures and workpiece accuracy issues. Lack of a virtual machining environment, to efficiently obtain the instantaneous un-deformed chip geometry and predict cutting forces in face-hobbing, results in undesirable production costs in industries. In the present paper, numerical and semi-analytical representation of the projection of the un-deformed chip on the rake face of the cutting blades is presented. The proposed approach is drastically fast and more accurate in comparison with numerical methods and can be implemented in a virtual gear machining environment. The cutting system intricate geometry, multi-axis machine tool kinematic chains and the variant cutting velocity along the cutting edge are taken into consideration to obtain the chip geometry efficiently. Then, cutting forces are predicted during face-hobbing by implementing oblique cutting theory using the derived chip geometry and converting face-hobbing into oblique cutting.

Usui's tool wear model [1] is implemented in face-hobbing using the predicted cutting forces. Using the proposed methods to predict cutting forces, interface temperature and normal stress along the cutting edge, the tool wear model is used to derive the most appropriate machining settings (cutting system rotary speed and plunge time) by optimization methods. In the optimization problems, the machining time is minimized and tool life is maximized. The proposed methods are applied on two case studies of face-hobbing of bevel gears and machining settings are adjusted.

Main Idea:

In order to implement optimization problems to derive appropriate machining settings, face-hobbing needs to be simulated computationally efficiently. One of the most important characteristics of face-hobbing simulation is predicted cutting forces. To estimate cutting forces, un-deformed chip geometry should be obtained. In order to do so, kinematic chain of the process should be defined. In the following, each procedure is described briefly.

Kinematic chains

Face-hobbing cutting system consists of a cutter head and bunch of cutting blades mounted in cutter head slots. In case of half profile cutting blades, one outside and one inside blade create a blade group. The cutter head and the workpiece rotate proportionally and cutter head approached the workpiece (plunge motion) as shown in Fig. 1. During the plunge motion, the cutting blades are engaged with the workpiece and removes material from it. When the offset to the back, BO, reaches zero, the plunge motion stops and the cutter head rotates Ng times to finish the gear teeth surfaces [2].

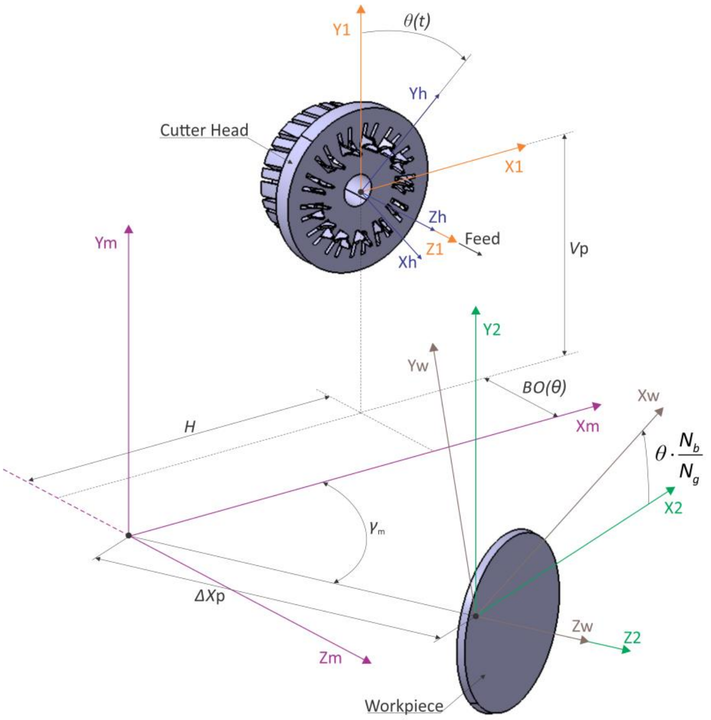

Fig. 1: Non-generated (Formate®) face-hobbing kinematics.

Un-deformed chip geometry

The projection of the un-deformed chip geometry on the rake face ,Ch_p, can be obtained using the numerical [3] and semi-analytic boundary theory. The boundaries of Ch_p, $\mathbf{C}_1$, $\mathbf{C}_2$, $\mathbf{C}_3$ and $\mathbf{C}_4$, are formulated by closed form equations in semi-analytical approach. Therefore, calculating the geometry of Ch_p is quite fast and computationally efficient. It should be noted that Fig. 2 shows the chip geometry in non-generated face-hobbing.

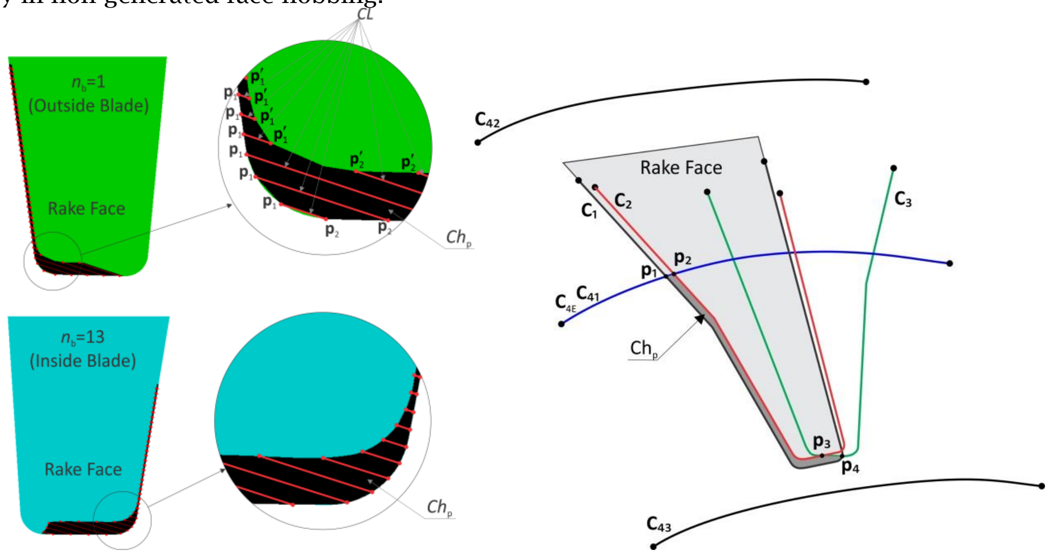

Fig. 2: The projection of the un-deformed chip geometry, Ch_p, on the rake face, Left: Numerical method [3], Right: Semi-analytical method [4].

Cutting force prediction

The cutting edge and derived Ch_p is discretized into many small cutting elements which each of them represents an oblique cut. In other words, face-hobbing is converted into many infinitesimal oblique cuts. The cutting forces for each differential element is calculated and the summed together to obtain the total cutting forces [3]. The cutting forces paly important role in tool wear rate calculation since the normal stress along the cutting edge is obtained using the differential cutting forces.

Wear rate model

In the present paper, in order to predict calculate the wear rate, Usui' wear rate model [1] is implemented in the optimization problems. The Usui's model is formulated as

$$\dot{w} = \frac{dw}{dt} = A \cdot \sigma_n \cdot V_s \cdot e^{\left(-\frac{B}{T_{\text{int}}}\right)}, \tag{1}$$

where w volume loss per unit area, $\dot{w}$ is volume loss per unit area per unit time, σ_n is normal stress, V_s is the chip sliding velocity relative to the workpiece, T_{int} is the interface temperature and, A and B are constants for given workpiece and cutting tool materials. In order to have a good prediction of wear rate, $\dot{\boldsymbol{w}}$, on the rake or relief faces of the tool, V_s, σ_n and T_{int} should be estimated accurately. In the present paper, for each differential oblique cut element, average wear rate, $\bar{\dot{w}}$, is calculated by substituting average normal stress, $\bar{\sigma}_n$, and interface temperature, $\bar{T}_{\text{int}}$ ($\bar{\dot{w}} = A \cdot \bar{\sigma}_n \cdot V_s \cdot e^{\left(-\frac{B}{\bar{T}_{\text{int}}}\right)}$).

Case studies

In this section, two case studies are investigated to show the capability of the proposed methods in this paper in machining setting adjustment. Case I is conducted to control the produced cutting forces by changing the machining settings. The workpiece and cutting tool materials are selected as Ti_6Al_4V and tungsten carbide, respectively [5,6]. The orthogonal cutting parameters are not velocity dependent since in Case I cutting velocity does not have large changes. In Case II, machining settings are adjusted to reach maximum possible tool life and minimizing the machining time. The proposed methods in this paper, to predict cutting forces normal stresses and interface temperature in the wear rate model, are applied in this case study. The workpiece material is AISI 1045 241HB. The orthogonal cutting parameters for this material, which are velocity dependent, are retrieved from CUTPRO® software [7].

Case I: Optimization considering cutting force limit

The purpose of this case study is to demonstrate the cutting force regulation in face-hobbing. In this problem, the process without optimization has a constant acceleration. Since the cutter head rotary speed for all cases are kept the same, cutting cycles happen at the same time for all cases. Fig. 3 shows the predicted cutting forces for constant and linear accelerations. As it can be seen, with linear acceleration (black line) the cutting forces smoothly and gradually increase (this gradual increase is also reflected in un-deformed chip geometry area (A_c)). However, the maximum cutting force (3.4 kN), which happens at the last cutting cycle (cutting cycle d), is 1 kN even higher than the maximum cutting force for the constant acceleration case ("Cons. Acc."). In order to decrease the cutting forces for linear acceleration case, the optimization problem is solved to minimize the plunge time while keeping the maximum cutting forces less than a threshold value (F_{max}<F_{all}=1.8 KN). The minimized machining time is about 73 sec. The predicted cutting forces for this solution are shown in Fig. 3 as "Opt. Linear Acc.". As it can be seen, the cutting forces increases very slowly and smoothly during 11 cutting cycle where the maximum force (1.8 kN) happens at the last cycle (k).

Case II: Optimization considering tool wear

The maximum crater wear depth was suggested to be less than 0.1mm in literature [3]. This value is considered as the optimization constraint in such a way that crater depth must be less than 0.1mm. Angular velocity of the cutter head and plunge time are set as $\omega \in \left[400, 900\right]$ RPM, $t_p \in \left[0, 40\right]$ sec, respectively. Now the optimization process begins (an outside blade is considered for optimization of face-hobbing of a sample gear). Each combination of cutter head angular velocity and plunge time creates a single machining scenario. For different scenarios, a MATLAB® code obtain the maximum tool wear rate ($\dot{w}_{\max}$) along the cutting edge (usually $\dot{w}_{\max}$ occurs at the tool tip and corner). Fig. 1 shows maximum wear rate vs. plunge time for different scenarios (each point represents a face-hobbing machining scenario).

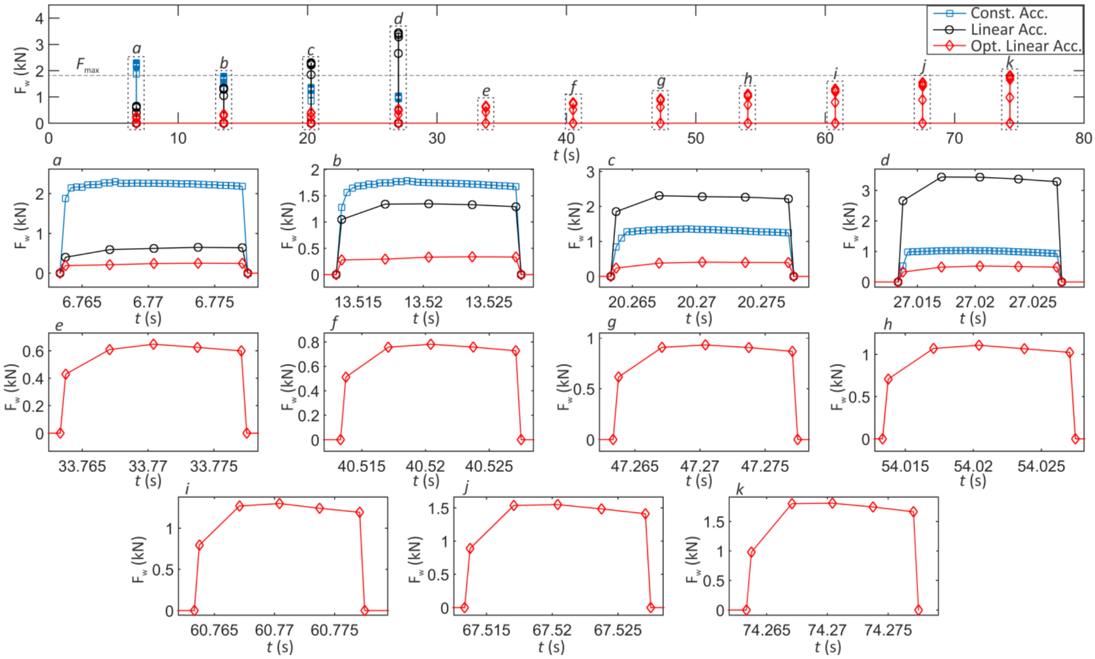

Fig.3: Predicted cutting forces in Case I.

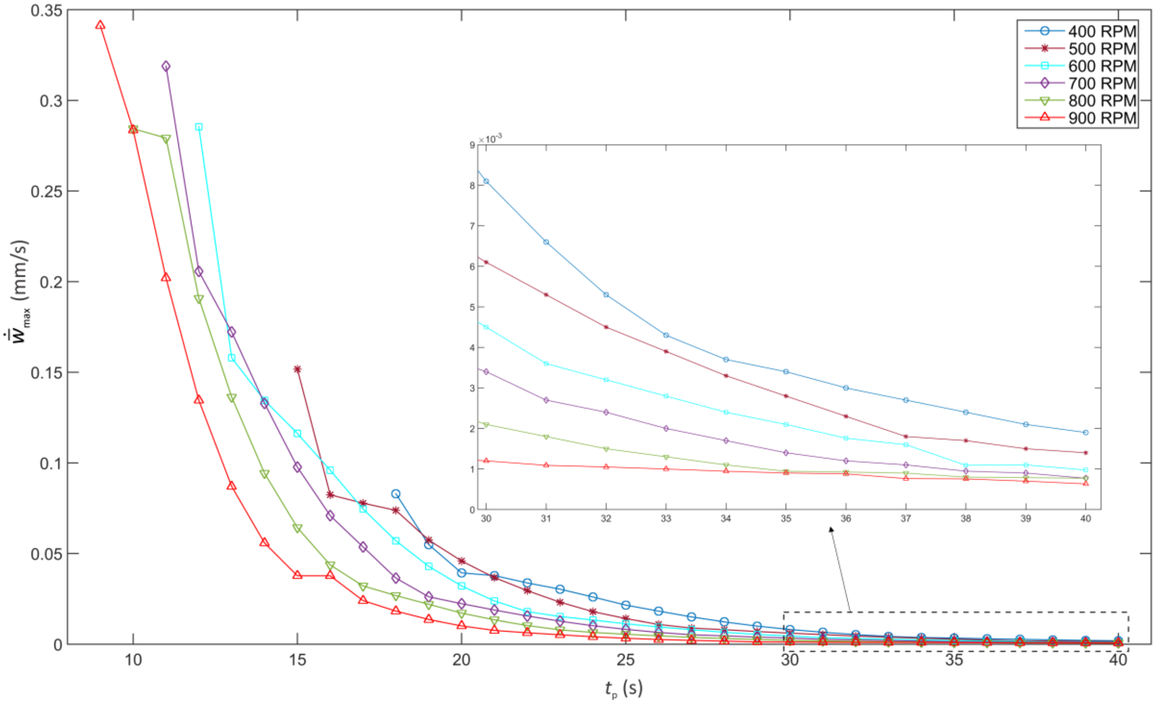

Fig. 4: Predicted maximum tool wear rate in Case II.

Conclusions:

In the present paper, tool wear rate model is implemented to select appropriate machining settings in face-hobbing of bevel gears in order to minimize the machining time and maximize the tool life. Un-deformed chip geometry, cutting forces, interface temperature and normal stress are predicted using proposed numerical and semi-analytical methods. Optimization problems are constructed using the cutting forces and tool wear rate models. Two case studies are investigated to demonstrate the ability of the proposed methods to select optimum machining settings.

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