Machining quality improvement and noise reduction of vehicle gears

Yu Bagaiskov

1Volzhsky Polytechnic Institute (branch) of Volgograd State Technical University, 43a Engelsa st, 404130, Volzhsky, Volgograd Region, Russia

E-mail: instra-ysb@rambler.ru

Abstract. Gear honing is a method to ensure high quality of vehicle gear teeth lateral faces used primarily for batch and mass production. Gear hones are used for this operation. Both the service life of vehicle systems and the vehicle noise level depend on the gear’s parameters accuracy and machining quality. Effectiveness of using gear hones depends mainly on the hardness and elasticity modulus of their composite material. In terms of the elasticity modulus, gear hones can be hard and elastic, depending on the bonding agent type. Some increase in roughness of the gear teeth lateral faces was observed at decreased hardness of the hard gear hone material due to accelerated pitting of abrasive particles. As the gear hone material elasticity degree increased with simultaneous hardness decrease, roughness decreased significantly, even at an increased abrasive grit size, as a result of alignment of the abrasive grain peaks along the supporting surface, extended contact time of the grains and machined surface, contact pattern area and fullness of machining; a favorable grid of machining marks is available. Though removal of such coarse irregularities as dents and burrs by hard gear hones is more efficient. Overall reduction of the noise level of vehicle gears is observed, as well. Correspondence of the obtained experimental results to the suggested theoretic criterion of quality and machining fullness.

1. Introduction
Gears are used in most designs of trucks and cars, mainly as part of speed-change gearboxes, hub drives, and drive shaft units [1, 2].

Both the operational life of the vehicle systems and the noise level depend on gear manufacture quality, which includes the accuracy of parameters, machining quality, especially those of teeth lateral faces [3-5].

Vehicle gears are made of high-quality alloyed steel grades with subsequent heat treatment at surface hardness HRC 50 – 65. Both grinding (for a small batch of high-accuracy components) and gear honing (in case of mass production of vehicles and medium-accuracy gears, correspondingly) are used to ensure high quality of gear teeth lateral faces. Gear hones are used as tools for gear honing [6, 7].

A gear hone is an abrasive tool for finish machining of hardened gear teeth lateral faces; it is manufactured using resin (epoxy, urethane) bonds. As a rule, it has the form of a helical gear and operates according to the generating method with reverse rotation and longitudinal feed [8 – 11].

It is necessary to estimate the influence of gears on machining quality and the noise level after honing by gear hones with various values of the abrasive grit size, hardness, and the tool material elasticity modulus.
2. Materials and Methods

The effective part of such abrasive tools is made of a composite material representing a cured polymer system filled with abrasive grains (a grinding material) of various sizes and obtained by casting with a particular set of properties different from those of the initial components [12]. White fused alumina 24A with abrasive grits F60 (250 µm) and F120 (60 µm) [13] is used for commercial production of gear hones.

The effectiveness of using such tools depends mainly on their composite material’s mechanical properties including hardness and the elasticity modulus [12]. In terms of the composite material elasticity modulus, depending on the bonding agent type, gear hones can be hard ($E_0 = 3000 – 6000$ MPa) and elastic ($E_0$ is 1000 MPa at least). Hardness of the gear hone material was determined according to the depth of indentation, using a sand-blast device. The deeper the dents are, the higher hardness is.

The influence of the hone-gear engagement geometry and the physical and mechanical properties of the gear hone material on the roughness value, machined surface completeness (absence of black spots), submicrorelief, and mark grid structure was estimated in the course of studying quality of the gear teeth faces after gear honing. Since gear honing is a low-temperature process which does not affect variation of the machined material’s properties, micro-hardness of component teeth was not studied. In the long run, the influence of all the factors on the noise level reduction was evaluated.

Roughness $R_a$ of the gear teeth machined faces was determined within the accuracy of 0.01 µm, using a profilograph-profilometer, mod. 252, the noise level — using a Hofler integrated device.

3. Results

The decrease value of roughness $\Delta R_a$ after machining by quite hard gear hones with the elastic modulus exceeding $E_0 = 3000$ MPa, made of the grinding material 24A F60/F120, was 0.6 – 0.8 µm regardless of their geometry variation.

The relation between the decrease value of roughness $\Delta R_a$ and the gear hone material hardness is shown in Figure 1. Some decrease of $\Delta R_a$ at decreased material hardness (increase of the depth of indentation $h$) results from increased pitting of abrasive grains from the bond and subsequent formation of a less dense grid of marks.

![Figure 1. Relation between decrease of gear teeth face roughness $\Delta R_a$ after gear honing and the gear hone material hardness $h$.](image-url)
As elasticity of the gear hone composite material increased (decrease of $E_0$), the roughness value of the machined surfaces decreased significantly (Figure 2). This resulted from alignment of the abrasive grain peaks along the supporting surface, extended contact time of the grains and machined surface, availability of bending and contact deformations [14, 15], significant increase of the contact pattern area of the hone teeth and gear, simultaneous use of multiple abrasive grains for metal cutting, and certain decrease of the average cutting depth. Besides, the influence of the grinding material grit size on roughness decreased at reduced $E_0$.

![Figure 2](image)

Figure 2. Relation between decrease of gear teeth face roughness $\Delta R_a$, and the elasticity modulus $E_0$ of the gear hone material manufactured using a grinding material of the grade 24A and grit sizes F120 (1) and F60 (2).

The relations between decreased roughness of the gear teeth face and the elasticity modulus are specified for the accuracy level of nearly 95%:

- For the grit size F120:

$$\Delta R_a = -2E - 10E_0^3 + 6E - 07E_0^2 - 0,0007x + 1,6891$$

(1)

- For the grit size F60:

$$\Delta R_a = 8E - 08E_0^2 - 0,0005E_0 + 1,417$$

(2)

The empirical relations $\Delta R_a = f(h_s, E_0)$ confirmed the analytical study results and the relation obtained in the course of modeling, applying the "roller analogy" method.

Use of elastic tools ensures high quality of the gear teeth faces over a shorter gear machining cycle, so machining capacity increases. For instance, using a gear hone with $E_0 = 500$ MPa (the grinding material of grade 24A, grit size F60/ F120) resulted in roughness $R_a = 1.0 \mu m$ for 1 – 2 double strokes of the gear hone, with $E_0 = 3000$ MPa — for 3 – 4 double strokes, roughness below $R_a = 0.63 \mu m$ was ensured only by an elastic gear hone (Figure 3). However, it is more efficient to remove coarse irregularities (dents and burrs) larger than $0.25 – 0.3 \text{ mm}$ by a gear hone with $E_0$ exceeding 1000 MPa.

Completeness $\Delta S$ of the gear tooth machined face is estimated by the absence of non-machined areas as a ratio of the machined face area to the initial area ($\Delta S \rightarrow 100\%$).

The relation between completeness of the gear teeth machined face, elasticity modulus, and gear hone material hardness was studied. Elastic gear hones ($E_0 = 100 – 1000$ MPa) are the most effective.
as they provide a larger contact pattern area in the tooth engagement. It accelerates reaching completeness of the machined surface.

\[ R_s, \mu m \]

![Figure 3. Variation of roughness \( R_s \) of the gear tooth machined face depending on the number \( n \) of gear-hone double strokes at \( E_0 = 3000 \) (1) and 500 MPa (2).](image)

The time required for hard gear hones to reach machining completeness (\( \Delta S = 100 \% \)) of gear teeth depends on hardness of their material (Figure 4). High quality of gear faces is ensured faster at higher hardness (higher \( h_s \)).

\[ \Delta S, \% \]

![Figure 4. Completeness of the gear teeth machined face (\( \Delta S \rightarrow 100 \% \)) at gear hone material hardness \( h_s = 1.3 \) (1) and 0.55 mm (2) depending on the number of components.](image)

Availability of a specific grid of marks after gear honing ensures favorable conditions for lubrication of the gear teeth faces and increases their load capacity and durability for operation in various mechanisms and vehicles.

Samples of gears made of the steel grade 40X, HRC 53 – 58, after machining by a gear hone with an elastic bonding agent (\( E_0 = 500 \) MPa) were used to study the submicrelief of the machined faces.
The machined surface areas were examined, using the 7000-power electronic microscope EMMA-2. Distinct cutting marks (small uniform marks) and partial signs of plastic deformation are present, which evidences favorable conditions for surface relief formation.

4. Discussion
The contact pattern area is the main parameter generalizing the influence of multiple factors on gear quality after gear honing. It depends on the hone and gear geometry, hone material elasticity modulus, and paired relationship of the contacts.

As contact pattern area of hone and gear teeth extends, the number of abrasive grain peaks involved in metal removal increases, the grid of machining marks becomes denser, and quality of the resulting faces increases. That is why the ratio of the contact pattern area $S_{w1}$ near the pole and the reference area $m^2$ ($m$ — the engagement modulus) characterizing the machined surface is used for the theoretical roughness optimization parameters:

$$K_s = \frac{S_{w1}}{m^2} \rightarrow \text{max}$$

(3)

The experimental research confirmed the relations between optimization criteria of gear honing and the hone material elasticity modulus obtained in the course of analytical modeling.

Figure 5 shows dependence of the theoretical criterion $K$ reflecting variation in roughness of the gear teeth faces after gear honing and the empirical value of gear face roughness decrease on the tool material’s elasticity modulus $E_0$. The theoretical and empirical relations are similar in the nature and value of variation.

5. Conclusions
In general, the research revealed some increase in roughness of the gear teeth lateral faces was observed at decreased hardness of the hard gear hone material due to increased wear and accelerated pitting of abrasive particles.

Roughness decreased significantly, even at a larger grit size, as the elasticity degree of gear-hone materials increased, i.e. if elastic gear hones were used; at the same time, hardness decreased due to alignment of the abrasive grain peaks along the supporting surface. The contact time of the abrasive
grits and surface increases, the contact pattern area becomes larger, the machining completeness degree increases, availability of a favorable grid of marks is confirmed. Besides, removal of coarse irregularities, dents, and burrs by hard gear hones is more efficient. Overall reduction of the noise level of vehicle gears by 3 – 5 dB is observed. The research revealed primary influence of the elasticity modulus of the gear-hone material on decrease of gear teeth roughness.

Correspondence of the results of the theoretical and experimental research confirmed validity of the suggested criterion enabling consideration of gear hone teeth deformation and subsequent variation of the contact pattern area.

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