Influence of elastic deformation of gear hone teeth on machined gear accuracy

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Abstract. The material of resin-bond gear hones becomes deformed during operation. The gear hone tooth deformation value depends on the contact point position along the tooth height; it increases by ten folds from the lower point to the top. The deformation values are comparable with metal removal volume and the initial error values of the machined parts. Besides, the kinematic parameters of engagement vary, the values of specific sliding and contact pattern areas are distributed along the part teeth height more uniformly. This should affect the nature and the correction values of gear errors after machining. Experiments proved that accuracy of gears after machining by hones depends on the initial accuracy degree of gears and hones, the paired relationship of geared contacts, the value and nature of distribution of the gear-teeth initial error, machining time. Errors can be intentionally rectified by using gear hones with various elasticity degrees depending on the initial accuracy of parts.

A gear hone is an abrasive tool for finish machining of hardened gear teeth lateral faces; it is manufactured using resin (epoxy, acrylic, urethane) bonds [1, 2]. In terms of geometry, is represents, as a rule, a helical gear consisting of a metal hub, a working part, and an abrasive-polymer ring gear. A gear hone operates according to the generating method with reverse rotation and longitudinal feed [3, 4, 5].

Due to the significantly lower elasticity modulus as compared to metal gears, the gear hone teeth material becomes deformed during operation. Besides, total deformation of gear hone teeth in the engagement line direction, similarly to gears, consists of contact deformation, flexural deformation of teeth, and tooth root deformation in the hone rim [6].

The total deformation analysis revealed that contact deformation prevails in lower contact points. The share of bending deformation and bedding deformation is increased in the pitch circle area to the level of contact deformation. At the tooth tip, total bending deformation is 4 times as high as contact deformation and reaches 70 % of total deformation [7].

Comparing the elastic deformation values of gear hone teeth with the errors of the gears processed (profile error \(f_p = 0.02 - 0.03\) mm for average-sized gears of accuracy degree 7 – 8) and the metal removal values (0.005 – 0.020 mm), it may be concluded that they are commensurate at hone material elasticity modulus \(E_0 < 6000\) MPa [8].

Deformation of gear hone teeth causes variation of their operation conditions, sliding parameters (speed and specific sliding), and sizes of the contact pattern with the machined gear faces [9]; the
values of such parameters are distributed along the gear tooth height more uniformly than those disregarding deformation [8].

Influence of the hone material elasticity modulus on accuracy of the machined gears was studied for experimental validation. Initial gear accuracy and consistency of gear error distribution were considered during the studies.

According to the effective regulations, accuracy of gears was evaluated according to the standard values of kinematic accuracy, smoothness of operation, and contact of geared teeth applying the following parameters: maximum tooth-to-tooth variation at single gear revolution ($F_r$), accumulated pitch error ($F_p$), difference between pitches ($f_{vp}$), tooth profile error ($f_r$), and tooth alignment error ($F_{\beta}$). The studies included machining of gears with accuracy degrees 7 — 8 and 5 — 6 by abrasive gear hones with various degrees of elasticity ($E_0 = 100 — 3000$ MPa) in gear-honing machines; with no consistency of distribution of the gear tooth profile error throughout the height.

The error values before and after machining were measured using devices for integrated monitoring of gears by Höfler (FRG).

The error rectification degree after machining by gear hones was assessed as a ratio of error value variation to the initial value applying the rectification ability parameter ($J$).

The values of $J$ for the main errors of machined gears are determined depending on the elasticity modulus of the gear hone materials ($E_0 = 100 — 2000$ MPa) after 3 and 9 double hone strokes in relation to the gear (Figure 1).

The study included machining of gears with accuracy degree 7 — 8 without regular distribution of the profile errors along the tooth height. Gear geometrics: $m = 4.25$ mm, $\alpha = 20^0$, $z_1 = 27$, $\beta_1 = 0^0$, $x_1 = 0$. Initial gear errors: $F_r = 0.09$ mm, $F_p = 0.025$ mm, $f_{vp} = 0.014$ mm, $f_r = 0.027$ mm, $F_{\beta} = 0.013$ mm.

The maximum increase of gear accuracy after gear honing was 30 — 40 % (Figure 1). As the elasticity modulus $E_0$ of the gear hone material decreases from 2000 to 100 MPa in case of machining during 3 double strokes with metal removal of 0.015 — 0.02 mm of gear thickness, the average values of the stroke accumulated error $F_r$ decreased by 10 %, the stroke difference $f_{vp}$ and the gear direction error $F_p$ decreased by 6 %. Besides, the gear profile error $f_r$ decreased by 8 — 9 %; $J = \max$ is reached at $E_0 = 500$ MPa. At lower values of $E_0$, the rectification value of this error is slightly lower due to edge engagement. The rectification degree of maximum tooth-to-tooth variation $F_r$ at single revolution decreased from 35 % to 22 % at a lower value of $E_0$, which is attributed to the decreased value of metal removal along the center-to-center distance wherein this error is rectified.

The dependence equations of the rectification degree $J$ of the mentioned gear errors, in particular, the maximum tooth-to-tooth variation at single gear revolution (1), the accumulated pitch error (2), the profile error (3), the difference between pitches (4), and the tooth alignment error (5), resulted from the elasticity modulus value of the gear hone composite material with minimum certainty of 0.99 appear as follows:

\[
J_1 = -2E - 06E_0^2 + 0,00113E_0 + 19,825; \quad (1)
\]
\[
J_2 = -0,0053E_0 + 38,578; \quad (2)
\]
\[
J_3 = -0,0042E_0 + 18,266; \quad (3)
\]
\[
J_4 = 5,5; \quad (4)
\]
\[
J_5 = 1E - 06E_0^2 - 0,0046E_0 + 16,951. \quad (5)
\]
In case the machining time is increased up to 9 double strokes, which increases the removed metal value up to 0.025 — 0.04 mm, the average increase of the error rectification ability \( F_r \) was 11 % in case of machining by a hard gear hone \( (E_0 = 2000 \text{ MPa}) \) and 7 % in case of machining by an elastic gear hone \( (E_0 = 100 \text{ MPa}) \). The error rectification degrees \( F_r \) and \( f_{pr} \) decreased to \( J = 8 \) and 5 %, correspondingly, without regard for \( E_0 \).

Figure 1. Dependence of the gear error rectification ability \( J \) on the elasticity modulus \( E_0 \) of the gear hone material: a — maximum tooth-to-tooth variation at single gear revolution (1) and variations of the accumulated pitch error (2); b — variations of the profile error (3) difference between pitches (4); c — variations of the tooth alignment error (5); ____ — during 3 double strokes; ------ — during 9 double strokes.
The nature of dependence $J = f(E_o)$ for the profile error did not change at extended machining time; however, the average rectification value at $E_o = 2000$ MPa decreased by 12% and increased by 5% at $E_o = 500$ MPa. The error rectification efficiency $F_r$ increased by 4% approximately for the whole range of the elasticity modulus $E_o$ values.

Thus, the theoretic provisions regarding applicability of increased-elasticity gear hones to decrease errors of gear teeth with accuracy degree 7 — 8.

It should be noted that further increase of the machining time (up to 15 — 20 double strokes) along with simultaneous increase of the removed metal layer results in gradual decrease of the rectification ability $J$ and even in increase of errors for a number of parameters ($F_{r1}$ and $F_{r2}$) as compared to the initial values. This can be explained by decrease of the error redistribution frequency among teeth as the conditions of such reallocation become worse with a decreased number of parts machined by a gear hone per unit time. It was made clear that the number of gear errors during gear honing, applying the generating method, is decreased only at lower values of the removed metal layer.

Noise monitoring of gears in pair engagement before and after machining by gear hones revealed noise decrease by 2 — 4 dB at $E_o = 2000$ MPa and by 3 — 4 dB at $E_o = 500$ MPa, i.e. at increased elasticity of the gear hone material. This resulted from efficient impact of elastic gear hones on accuracy of the geometry parameters and quality of the gears’ working faces.

Thus, the theoretic provisions regarding the influence of varying values of specific sliding and contact pattern areas of the hone and gear teeth, considering deformation of gear hone metal, on involute-profile accuracy of gear teeth have been confirmed by experiment.

Despite uneven variation of the sliding speed of hone and gear teeth along their height and lower accuracy of gear hones as compared to that of machined gears (with degree 1 — 2), the number of teeth profile errors is decreased in most cases after gear honing.

The studies showed that gear accuracy after gear honing is ensured at restricted values of the removed metal layer and machining time depending on the elasticity degree of the gear hone materials. Increase in accuracy of gears with no consistency of distribution of the initial errors occurs at decrease of $E_o$ down to 100 — 500 MPa.

Due to more favorable load distribution in engagement of the gear and hone teeth at increased elasticity of the gears, the error rectification ability of the gear profile with a two-pair contact between the hone and gear teeth is higher than that with a single-pair contact (Figure 2a).

![Figure 2](image)

**Figure 2.** Histograms of the profile error rectification ability $J$ depending on the paired relationship of contacts (a) and the accuracy degree of gear blanks (b) at $E_o = 3000$ (1) and 500 MPa (2)
The gear error rectification ability is attributed to redistribution of the error values among the gear teeth and thus averaging due to non-multiplicity of the number of the gear and hone teeth. The nature of error redistribution depends on initial gear accuracy and consistency of error variation. As shown in the histogram (Figure 2b), the higher accuracy of gear blanks is, the lower rectification ability is reached, but at the same time the efficiency of using elastic gear hones ($E_0 = 100 — 500$ MPa) is higher as compared to that of hard gear hones ($E_0 = 3000 — 5000$ MPa). For example, the rectification ability values for gears with accuracy degree 7 amount to 25 % and 20 %, correspondingly, with accuracy degree 5 — approximately 0 % and -28 %; in other words, hard gear hones make the gear profile worse and elastic gear hones do not change the profile.

Basically gear-hone teeth can be machined prior to operations up to accuracy degree 6 — 7. Feasibility of such a labor-intensive process (regrinding during operation is required) can be determined using the histogram shown in Figure 3. Grinding of the gear hone teeth profiles can be practical only in case of machining of gears with strict requirements for accuracy.

Besides, additional studies revealed the possibility to intentionally affect decrease of errors by using gear hones with different elasticity degrees, considering consistency of distribution of the gear profile errors before gear honing. The following gears were machined: type 1 — accuracy degree 7 or 8, made of improved chrome-nickel steel with hardness HRC 58 — 62, after nitrocarburizing (no apparent consistency of profile error distribution); type 2 — accuracy degree 7, made of chrome-vanadium steel with HRC 56 — 58, after high-frequency hardening (plus deviation at the tooth tips); type 3 — accuracy degree 7 or 8, made of chrome-manganese steel with HRC 58 — 60, after case hardening (plus deviation at the roots); type 4 — with increased accuracy (degree 5 or 6), made of very hard steel with HRC 60 — 63, after nitriding.

![Figure 3](image.png)

**Figure 3.** Histogram of variation of the gear-tooth profile error rectification ability $J$ at various accuracy degrees in case of machining by gear hones with accuracy degrees 9 — 10 (1) and 6 — 7 (2)

Despite absence of consistency of profile error distribution for parts with accuracy degree 7 — 8, the profile error $f_p$ was decreased both by hard ($E_0 = 3000$ MPa) and elastic ($E_0 = 500$ MPa) gear hones, yet the rectification degree is slightly higher in the latter case.

In case of a positive deviation of the error $f_p$ at the tip (part 2), a hard gear hone scarcely improved gear accuracy, but an elastic gear hone improved gear accuracy by 25 %. Otherwise, in case of a positive deviation of the gear profile error at the root (part 3), a hard tool, with the material elasticity modulus $E_0 = 3000 — 6000$ MPa, is more efficient as it removes more metal exactly from the tooth roots.
In case of machining of gears with increased accuracy (part 4) by hard gear hones, decrease of gear accuracy after gear honing was confirmed; besides, distortion of the tooth profile was observed. In case of using gear hones with high elasticity ($E_a = 100 — 500$ MPa), the value of $f_{fr}$ remained nearly the same.

Thus, it was generally demonstrated that gear accuracy after gear honing depends, in each particular case, on the initial accuracy degree of both gears and gear hones, the paired relationship of geared contacts, the value and nature of distribution of the initial errors of the gear teeth, the machining time; it can be intentionally rectified by using gear hones with various elasticity degrees, primarily, elastic gear hones.

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