Surface topography of cylindrical gear wheels after smoothing in abrasive mass, honing and shot peening

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Abstract. The present paper presents the analysis of surface topography of gear teeth as the result of final machining processes. Teeth of multiple cylindrical gears shaped by grinding were smoothed in abrasive mass, honed or shot peened. The measurement of gears were made using coordinate measuring machine and 3D surface topography stylus instrument. The following deviations were studied; pitch deviation, total pitches deviations, variation of teeth thickness and deviation of gear radial run-out. Changes in teeth surface topography during machining process were determined. 3D surface topography parameters, surface directionality as well as areal autocorrelation and power spectral density functions were taken into consideration. As the results of the analysis, the best surface topography with regard to gear operational properties was recommended.

1. Introduction
The analysis of surface topography makes possible control of production process, prediction and optimization of machine elements functional properties [1]. It is widely known that method of gear tooth finishing and its surface topography highly influences gear fatigue life, its resistance to motion, vibration and noise [2-12]. Small value of power spectral density of teeth flanks surface topography assures little generated noise and vibration level of gear [11]. So it is desirable to optimize gear geometry. The problem of assessment of gear surface topography is of great practical importance.

Toothed wheels can be created by decrement, volumetric and incremental methods. It is required during contemporary gears production to carry out many tests, analyses and measurement. There are the following popular methods of toothed wheels finishing in soft and hard states: grinding, shaving, honing, super-finishing, lapping, shot peening, burnishing, electrochemical machining, chemical-abrasive treatment, magneto-chemical machining and others. The progress of shot peening [3, 4, 6], grinding [2, 7, 10, 13-15] and chemical-abrasive machining is the highest [9, 12].

2. The aims and scope of the investigations
Semi-finished products of toothed shafts from alloy low-carbon carburizing steel of AMS 6308 type were made by die forging method. Gear envelopes were quenched and tempered to hardness of 35–40 HRC. Module pitch of a gear in normal section was 1.90598 mm. Table 1 presents the characteristic of the analysed gears with their requirements.

| Specification toothed wheel rim | Value |
|---------------------------------|-------|
| 1. Diametric pitch transfer plane, mm | 2.03200 |
| 2. Diametric pitch normal plane, mm | 1.90598 |
| 3. Normal pressure angle, ° | 25 |
| 4. Width toothed wheel rim, mm | 34.23 |
| 5. Pitch diameter circle, mm | 50.80000 |
| 6. Root diameter circle, mm | 46.2534–46.1518 |
| 7. Number of teeth, - | 25 |
| 8. Form diameter circle, mm | 47.4472 |
| 9. Base diameter circle, mm | 46.0404 |
| 10. Tooth fillet R, mm | min. 0.559 |
| 11. Form diameter roll angle, °, ′ | 32°11′ |
| 12. Based on chordal tooth thickness, mm | 3.1877–3.2385 |
| 13. Reference data measurement over, mm, diameter wires 3,6576 mm | 56.9264–56.8299 |

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Gear teeth created by Sykes chiseling were subjected to carburizing, hardening, low-temperature treatment and tempering. Then grinding by shape method Kapp was executed with application of machine VAS 432 CNC with control system Optromic CNC-D140. Pitch feed of rough grinding was 0.05 mm per dual stroke of reciprocal motion, but longitudinal feed was 500 mm/min. Chemical-abrasive treatment of gears was made by smoothing in abrasive mass using machine made by Almco, model 29F-48A. This type of machining was done for both wheels after rough grinding by Kapp method as well as gears after rough and finish grinding. The first group (after rough grinding and smoothing) of toothed wheels was subjected to honing, but the second (after rough and finish grinding and smoothing) to shot peening. Five toothed shafts for each type of machining were tested.

Gear teeth honing was made using Fässler machine model D-250. Honing tool rim, of a teeth helical line slope 8º was equipped with abrasive material from aloxite with resinous binder 42A 180 R-5B. Shot peening was executed with steel balls S110 (of about 0.23 mm diameter) of Wheelabrator Allevard firm. Dry jet device using negative pressure method of Vapor Blast firm was used, VB 3576 type. The coefficient of surface coverage was 100%, shot peening intensity was F 13/17 A [3, 4, 6].

Stereometric shape of teeth sides was measured by coordinate measuring system CNC, model PNC 40 of Klingelnberg Söhne firm. Plunger finished by spherical surface of 1 mm radius was used. Table 2 presents the results of measurement.

### Table 2. Accuracy parameters of side gear surfaces after machining (in brackets standard deviations)

| Side of tooth deviations and run-out deviation | Finish grinding | Smoothing in abrasive mass | Honing | Shot peening |
|-----------------------------------------------|-----------------|----------------------------|--------|--------------|
| 1. Single pitch deviations $f_{pt}$, £m       | 2.3 (0.5)       | 1.6 (0.6)                  | 1.4 (0.3)| 1.5 (0.6)    |
| 2. Total cumulative pitch deviations $F_p$, £m| 5.3 (0.8)       | 5.2 (1.3)                  | 4.4 (1.1)| 4.3 (1.1)    |
| 3. Pitch line run-out $F_r$, £m               | 9.1 (2.3)       | 4.7 (2.1)                  | 2.2 (0.5)| 4.8 (2.2)    |
| 4. Maximum variation of the chordal thickness $R_s$, £m | 4.5 (0.5) | 5.1 (2.0)                  | 3.8 (0.6)| 5.1 (2.1)    |

Tables 3 and 4 present the results of measurement of teeth sides. Talyscan 150 contact equipment of Taylor Precision firm was used. Square surfaces of side length 3.072 mm were measured. Sampling intervals in perpendicular directions were 6 £m. Form was removed by polynomial of 8-th degree. No digital filtration was used. 512 contours of tooth profile and 512 contours of tooth line were numerically separated. Definitions of parameters are presented in standards ISO 25178 and ISO 4287.

### Table 3. Parameters of areal surface topography of tooth flank gears

| Surface parameters | Grinding | Smoothing in abrasive mass | Honing | Shot peening |
|--------------------|----------|----------------------------|--------|--------------|
| $S_z$, £m          | 1.30     | 0.26                       | 0.11   | 0.33         |
| $S_q$, £m          | 1.60     | 0.32                       | 0.14   | 0.42         |
| $S_p$, £m          | 6.09     | 2.40                       | 3.88   | 3.49         |
| $S_c$, £m          | 11.7     | 4.08                       | 6.04   | 6.01         |
| $S_{sk}$, -        | -0.05    | -0.24                      | 1.35   | -0.23        |
| $S_{ku}$, -        | 2.71     | 2.94                       | 27.40  | 4.20         |
| $S_{fit}$, £m      | 10.40    | 3.46                       | 4.41   | 4.77         |
| $S_{sv}$, -        | 5.61     | 1.68                       | 2.16   | 2.52         |
| $S_{tr}$, -        | 0.0389   | 0.0117                     | 0.0286 | 0.0421       |
| $S_{al}$, mm       | 0.0440   | 0.0158                     | 0.0295 | 0.0727       |
| $S_{td}$, °        | 4.0      | 4.5                        | 3.0    | 1.5          |
| $S_{fd}$, -        | 2.39     | 2.53                       | 2.26   | 2.46         |
| $S_{pd}$, 1/mm²    | 867      | 1843                       | 2505   | 1617         |
| $S_{sdq}$, £m/µm   | 0.0820   | 0.0356                     | 0.0175 | 0.0315       |
| $S_{spc}$, 1/µm    | 0.0120   | 0.0088                     | 0.0049 | 0.0055       |
| $S_{sd}$, %        | 0.3350   | 0.0634                     | 0.0152 | 0.0495       |
| $S_{sk}$, £m       | 3.40     | 0.77                       | 0.31   | 0.74         |
| $S_{sp}$, £m       | 1.21     | 0.24                       | 0.13   | 0.31         |
| $S_{sv}$, £m       | 1.63     | 0.30                       | 0.14   | 0.43         |
| $S_{sm1}$, %       | 9.9      | 7.4                        | 10.4   | 11.2         |
| $S_{sm2}$, £m      | 81.8     | 86.3                       | 88.4   | 87.2         |
3. Results and discussion

Accuracy of side surfaces of toothed wheel is the highest after Fässler honing. It results from the values of deviations: fpt, Fp and Fr. Maximum deviation Rs as well as standard deviations of the analysed accuracy parameters are also the smallest after honing. The values of side surfaces of toothed wheels after grinding by Kapp method also decreased after smoothing in abrasive mass and shot peening. Profile contours on tooth height after grinding are not smooth in geometric sense. During smoothing in abrasive honing and during shot peening the flank tooth surface topography changes are small. However Fässler honing makes possible to obtain smooth shape of tooth contour on its height. The other important property of honing is the possibility of creation of required tooth shape and also its changes in comparison to that obtained previously in grinding process.

Roughness height of teeth surfaces significantly decreased as a result of smoothing in abrasive mass after earlier grinding. Not only roughness height decreased, but also fastest decay autocorrelation length Sal, root mean square slope Sdq and arithmetic mean peak curvature Spc. Parameters characterizing material ratio curve: core roughness depth Sk, reduced peak height Spk and reduced valley height Svk also decreased.

Honing of gear teeth after rough grinding by Kapp method and smoothing in abrasive mass by Almco method assures the smallest roughness height. The lack of deep valleys and presence of not numerous peaks is its characteristic feature. It is also characterized by the highest obtained peak density Spd. Small values of the following parameters prove its profitable properties: root mean slope Sdq, peak curvature Spc, core roughness depth Sk, reduced peak height Spk and reduced valley height Svk.

Shot peening of teeth sides previously ground by Kappa method, smoothed in abrasive mass by Almco method, in small degree caused increase in maximum surface height Sz. Average height parameters Sa and Sq increased significantly. Autocorrelation length Sal and texture parameter Str also much increased. However skewness Ssk, kurtosis Sku and angle Std decreased. Surface directionality changes are small. However changes of power spectral density are high.

Profitable functional features of side teeth surface after Fässler honing were confirmed also by small height of contours of profile and line. That machining method creates also large profile spacing, PSm parameter value proves it. The profitable features were confirmed by the smallest slope Sdq and the smallest peak curvature Spc. Similar conclusions may be drawn from the analysis of profile and line slope.

Anisotropy of tooth side is rather high after shot peening (previously and after rough and finish grinding by Kapp method and smoothing in abrasive mass) - see values of the Str parameter. All the analysed machining methods create tooth flank surface of random-deterministic (quasi-deterministic) type. Autocorrelation function and power spectra density function pointed to high surface directionality along tooth side. Power spectral density is characterized by comparatively high values for large wavelength after grinding by Kapp method and smoothing in abrasive mass by Almco method. This surface is crossed with small angle. Fässler honing assured the smallest value of power spectral density. Power spectrum was separated particularly for large wavelengths.

After the analysis of angular spectra of areal autocorrelation and power spectral density functions one can see that angular positions of mean value of angular spectra (non modal value) are measures of surface direction. Quasi-periodical structure of machined tooth sides, particularly of high correlation length in tooth line direction caused that it is impossible to obtain information about surface directionality on the basis of cross-correlation function. For all the analysed machining methods areal autocorrelation function and power spectral density function present both surface directionality and characteristic of background. Similar assessment of surface directionality can be obtained on the basis of power spectral density and autocorrelation function, but the first of them seems to be better. Amplitude distributions after smoothing in abrasive mass by Almco method and shot peening by Vapor Blast method are similar to each other, but different distributions were achieved after honing by Fässler method.

Table 4. Parameters of profile and line contours of side tooth after machining

| Profile parameters | Contour of profile | Contour of line |
|--------------------|-------------------|----------------|
|                    | Smoothing in abrasive mass | Honing | Shot peening |
|                    | Smoothing in abrasive mass | Honing | Shot peening |
| Pa (μm)            | 0.26              | 0.11          | 0.30 | 0.26          | 0.11 | 0.30 |
| Pb (μm)            | 0.32              | 0.14          | 0.38 | 0.62          | 0.30 | 1.61 |
| Pp (μm)            | 1.26              | 1.00          | 1.19 | 1.26          | 1.00 | 1.19 |
| Pl (μm)            | 2.86              | 1.71          | 2.54 | 2.86          | 1.71 | 2.54 |
| Psk (-)            | -0.24             | 0.04          | -0.29 | -0.24        | 0.04 | -0.29 |
| Pku (-)            | 2.90              | 4.61          | 2.86 | 2.90          | 4.61 | 2.86 |
| Psm, (μm)          | 63                | 78            | 72   | 84            | 64  | 78  |
| Fa (º)             | 1.396             | 0.445         | 1.092 | 0.434        | 0.279 | 0.244 |
| Ddq (º)            | 1.786             | 0.593         | 1.404 | 0.593        | 0.414 | 0.370 |
4. Concluding remarks

Surface of honed tooth side in hard state, after previous rough grinding by Kapp method and smoothing in abrasive mass by Almco method is characterized by the smallest values of kinematic accuracy deviations \( f_{pt}, F_p, \) run-out \( F_r \) and chordal tooth thickness \( R_s \). This surface was recommended for gear of small resistance to motion, vibration and noise. Small roughness height and low power spectral density prove about profitable properties. The possibility of precise and reproducible modification of tooth profile along its height and tooth line along its width is the other advantage of Fässler honing.
The results of application of smoothing in abrasive mass and shot peening are similar with regard to creation of amplitude ordinate distribution of tooth side surface topography; however honing by Fässler method caused better ordinate distribution characteristics.

The highest possibility of modification of geometrical features of tooth side was found for teeth shot peening by Vapor Blast method after earlier rough and finish grinding by Kapp method and smoothing in abrasive mass. Shot peening is contemporary applied to finishing of tooth sides after pretreatment by honing. Kapp grinding assures high production efficiency. Presented production process of shot peening by Vapor Blast method assures similar tooth profile and line accuracies to these created in previous machining process – finish grinding. Although roughness height after shot peening is much higher that after smoothing in abrasive mass, changes in power spectral density values are small.

Similar and proper assessment of surface directionality can be obtained on the basis of power spectral density and autocorrelation functions, but the first of them seems to be better. Surface of tooth flank side after machining by the analysed method is anisotropic, it is also strongly oriented along teeth lines.

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