Improving the quality of manufacture of the differential pinion gears through the integrated application of statistical methods of quality management

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Abstract: An approach is proposed to ensure a stable spot size in the interfaces of the satellites with the central gear. Characteristics are proposed for estimating the position of the contact patch on the lateral surface of the tooth. The characteristics of the contact patch after circular broaching were analyzed using various statistical methods. The dependence of the characteristics and position of the contact patch on the tooth surface on a number of factors has been revealed. Proposed measures for their stabilization.

Keywords: gear, bevel gear, statistical methods, quality improvement, gear propelling operation.

1. Introduction
Conical spur gears are part of the reducer of the differential of heavy trucks. The differential ensures the independence of the rotation of the wheels of the car at different speeds of rotation. The design of the differential is such that in the process of redistributing the moment at the same time four satellites are installed, mounted on the crosspiece. In the process of working the differential, they simultaneously roll over the conical rims of two conical ribs, the internal splines of which are connected to the right and left axles, which in turn are connected by wheel hubs. Any deviations in the relative position of the bevel wheels, as well as the size of their holes, lead to violations of the relative position of the entire set of interacting bevel wheels, changing or redistributing the area of the total contact patch. The unevenness of the area and location of the contact spots on the teeth of the rims of the conical wheels can lead to uneven loading of individual teeth and their intense local wear. In some, the most unfavorable combinations of the operating modes of the car, their breakdown is possible. The importance of ensuring a given value and location of the total contact patch of a bevel gear in the differential mechanism is that it is unregulated. The deviations resulting from the technological process in the magnitude and distribution of the contact spots can not be compensated or redistributed by adjusting the position of the gears during the assembly of the differential. Thus, an indicator of the total contact patch of a set of four satellites can be considered an integral indicator of the quality of functioning of a differential.

Providing a total spot of contact for the entire satellite set is possible only if there are no deviations in the shape and size of their base holes, a predetermined level and relative position of the contact spots on the rims, no deviations of the relative positions of the holes of the differential cups, the size of the holes in the tapered wheels, and no in the deviations of the teeth of the gear rim of bevel gears.

This article deals with the quality management of the process of manufacturing a single satellite differential.

2. Theoretical part
The technological process of manufacturing a gear wheel consists of the following main operations, in which the shaping of individual elements is carried out: turning, roughing and finishing gear-driving operations, heat treatment operations, finishing boring operation, coating application. Starting with a gear-over operation, after making a crown of a bevel gear, each subsequent operation can change the relative position of its teeth, and therefore affect the size and relative location of contact spots. In the event that a contact patch of an inappropriate area and (or) location was initially obtained in a gear-over operation, subsequent operations can only worsen them or leave them...
unchanged. Therefore, it is precisely for the operations of draft and finishing gearing that it is important to ensure effective management of the manufacturing quality of the teeth of the satellite crown.

In production, the process of tooth processing is performed on machines ST 268 of the draft (Figure 1a) and finishing gearing (Figure 1b). They are rigidly connected with each other by an automated automated step conveyor (Figure 1.1 c) into an automatic line. During processing, the satellites move along the conveyor strictly in accordance with the beat. The capacity of the conveyor is 14 satellites. The satellite billet is installed by the auto operator into the expanding horizontal mandrel, the broach rotates around the vertical axis and receives a coordinated translational movement parallel to the line of the depressions of the gear wheel. Both machines are structurally similar, the difference lies in the performance of interchangeable sections of circular broach and copiers, defining the trajectory of their relative movement relative to the stretched workpiece.

In the process of toothing, it is necessary to ensure that the profile and the relative position of the side surfaces of the teeth of the ring gear so that the contact patch is located at the calculated point of the gear train [1] (fig. 3).

In the workshop conditions, under the supervision of the personnel, there is only one quality indicator of the satellite - the beating of the ring gear along the pitch circle, which is the only indicator for evaluating the technological accuracy of the drive-through automatic line, for measurements of which there is a special control device at the workplace. Evaluation of the size of the contact patch is carried out by visual comparison of the obtained contact patch with the allowed forms. Measurements and registration of its parameters is not performed. According to the same subjective assessments, the tool configuration is performed. A visual comparison of the acceptable forms and location of contact spots by experienced and qualified personnel ensures the suitability of the products produced, but in these conditions it is impossible to develop the content of corrective actions to improve the quality of the satellites of the differential.

The standard method of rationing the contact patch establishes the requirements for the size occupied by the contact patch in the direction of the tooth and its height [2]. Works [3-5] are devoted to the synthesis of transmission and profiling of the tool. He assumes that the contact patch is already at the
calculated point of the gear train, i.e. the toothing process is in an adjusted state (fig. 2 a). In practice, even in a well-established process of teeth processing, the total contact patch may significantly shift relative to the calculated point of the gear train (fig. 2 b), and in some cases may reach the edges of the teeth. To assess the location of the contact patch, the standard evaluation method is not applicable (fig. 2), as a result of which it is unsuitable for developing comprehensive recommendations for quality improvement [6]

Figure 2. The total contact patch of the contact of a conical gear train (a) the rationing of the size of the contact patch in a bevel gear I is the largest limiting size of the contact patch; II - nominal size of the contact patch; III - the smallest limit size of the contact patch [1,2] (b) photograph of the side surface of the satellite with the circumscribed boundaries of the contact patch.

Therefore, before developing a method for controlling the quality of the manufacture of gear rims in the toothing process, a method was developed to assess the compatibility of the gear teeth of the differential satellite in terms of both dimensions and the relative position of the total contact patch. As a result, in addition to the standard indicators characterizing the size of the contact patch relative to the length and height of the tooth % H, % L (fig. 3), the indicators L1, L2, L3, L4 were added - the distances from the extreme points of the total contact patch to the borders of the active tooth surface (fig. 4, 5).

Figure 3. The minimum and maximum allowable values of the indicators of the size of the total contact patch % H - along the height of the tooth, % L - along the length of the tooth.

Figure 4. The minimum allowable values of indicators of the relative position of the total contact patch L1, L2, L3, L4.
To find the whole complex of operating factors affecting the magnitude of the total contact patch, taking into account the results of a positive solution of similar problems in various processes of forming machine parts [7–11], the main key quality indicators were found, the values of which should be measured when production experiment.

Prior to the operation of draft gearing, it is the beating on the outer conical surface of the workpiece, as well as the internal diametrical size of the support element, by which it is mounted on the expanding mandrel. After the finishing operation, it is the beating on the middle dividing cone and the parameters of the contact patch (table 1).

### Table 1. Measurable Indicators and Measuring Instruments of Bevel Wheel Indicators

| #     | Operation   | Measurable Indicators                  | Measuring Instrument                     | Standard                      |
|-------|-------------|----------------------------------------|------------------------------------------|-------------------------------|
| 025-1 | Draft gearing | Middle Cone Runout                     | Control device. The indicator of hour type with the division value 0.01 mm | Gear crown of the reference satellite |
|       |             | Runout on the outer conical surface     | Control device. The indicator of hour type with the division value 0.01 mm | Gear crown of the reference satellite |
|       |             | Internal diameter                       | Nutrometer two-point. The indicator of hour type with the division value 0.002 mm. | Reference ring d=27.5 mm      |
| 025-2 | Fair handling | Middle Cone Runout                     | Control device. The indicator of hour type with the division value 0.01 mm | Gear crown of the reference satellite |
|       |             | Contact patch                           | Special gearing machine. The indicator of hour type with the division value 0.01 mm | Reference gear shaft axle rear axle |

Measurements of all indicators are carried out by shop measuring instruments. The setting up of tools is carried out using special standards and standard details available at workplaces.

To improve the effectiveness of the methodology [7], as well as the possibility of using the correlation method, a measurement scheme of the studied part was developed. Measurements of the billet and the processed semi-finished product are performed in a single coordinate system, for which its beginning is marked on the billet as a mark of the first tooth.

Measurement of the beats on the outer and dividing cone is performed for each tooth cavity, which receives its own sequence number (fig. 6 a).

Measurements of the internal diametrical size of the pre-bar element of the billet are made in two mutually perpendicular sections along the length along the length of the billet. The location of these sections is also known by reference to the numbers of the troughs (fig. 6 b).
The research method consists in the consistent application of various methods of analysis:

1. The primary analysis of measurement data. At this stage, the measurement data is checked for gross errors according to the Grubbs criterion. The histogram is executed. Preliminary check of the current law of distribution and calculation of statistical characteristics. In case of detection of measurement errors, they are eliminated or excluded from the calculation.

2. Probabilistic-statistical analysis is performed in several steps. The construction of the distribution curve. The indices of stability $C_p$ and mood of the process $C_p$, $C_p$ are calculated. The result of this stage is the final conclusion on the current law of distribution, as well as on the stability and mood of the technological process.

3. Control charts of individual values and sliding ranges. For a small sample with consecutive measurements belonging to one blank, this is the most optimal map view. It is carried out in several steps. Calculated values of control boundaries. The construction of paired control charts is performed, as well as the analysis of the position of points on the chart for specific reasons.

4. At the final stage of the analysis, the criterion of equality of the mean and standard deviations of the found values of the accuracy indicators, as well as the correlation analysis between pairs of accuracy indicators, is applied. The result of the application of the technique is the conclusion about the uniformity of the random and systematic factors acting in the technological process, as well as the conclusion about the presence of hereditary technological links between pairs of indicators of the quality of the satellite of the differential.

### 3. Practical implementation example

In order to obtain information on the effect of the main technological factors in applying the adopted measurement scheme and data processing technique, it is enough to measure no more than 3 parts. The main condition for the selection of parts - they must fall into the general population and do not differ in terms of production from the main volume of parts in the party. Such a number of details is necessary to eliminate the probability of possible random errors. Consider the results of the sequential application of various methods of analysis of radial beats on the dividing cone before and after the operation of finishing toothing (fig. 7, 8).

By the run-down of the pitch cone, no discrepancies were found before the operation of finishing gear removal. There were no blunders in these measurements. The distribution in form is also close to the equiprobable law (fig. 7 a). According to the charts of control charts, unusual series of points are identified: trends with a consistent decrease and increase in points (fig. 7 c, d). Such a change in the points of the graph can be associated with the error in positioning the mandrel when it is based and fixed in each position of the processing of the cavities of the teeth of the ring gear.

By the runout of the dividing cone, after the operation of the finishing gear removal, no discrepancies were also found (fig. 8a). There were no blunders in the measurement results. The distribution in shape is close to the Rayleigh distribution (fig. 8 b). The stability of the process is sufficient $C_p =$
1.789. Sharp changes in the values from the upper control border to the lower one in 0.02 mm (fig. 8c), indicating the presence of an error in spindle positioning in individual positions of the tooth groove machining, were found on the graph of the control card of sliding scales. Similar calculations and construction are performed for all indicators of the total contact patch. A general recommendation for them is the need to take corrective actions to improve the stability of indicators, both in terms of occupied area and relative position (Table 4). The greatest interest in terms of identifying hidden technological factors acting in the process of toothing is the correlation analysis. The results of the calculations of the correlation coefficients between pairs of indicators of the accuracy of the satellite differential are given in Tables 2 and 3. Cells with significant values of correlation coefficients are highlighted in dark color. The correlation coefficients were calculated between those pairs of indicators, the mechanisms of action between which can be assumed in advance.

Figure 7. The results of processing the measurement data in terms of the “runout of the pitch diameter” after the rough cutting. (a) histogram, (b) theoretical distribution curve, (c) control charts of individual values and sliding scales.

Figure 8. The results of processing the measurement data in terms of the “beating of the pitch diameter” after the pure tooth reprocessing. a) a histogram, b) a theoretical distribution curve, c, d) control charts of gliding scales and individual values.
For example, between the indicator “external conic beating” and “beating along the separating cone after draft gearing,” the correlation coefficient is 0.9, i.e. an increase in the external cone beating after a turning operation preceding a rough beating operation unambiguously leads to an increase in the beating along the separation cone after a rough operation, the protrusion.

It can be assumed that there is a hereditary technological relationship between these indicators. This relationship is possible if there is insufficient rigidity of the expanding mandrel of the roughing-out machine when the amount of the allowance varies in individual positions of the gearing. There is no correlation relationship between the beating along the separation cone after the operation of the rough and the finishing gear reproducing, which indicates a sufficient rigidity of the expanding mandrel of the finishing gear rolling machine.

Table 2. The values of the correlation coefficients between the indicators of the accuracy of the satellite differential

| Quality indicators | ECR | PCR_{dr} | PCR_{fin} | %L CW | %H CW | L1 CW | L2 CW | L3 CW | L4 CW | PCR_{dr} − PCR_{fin} |
|--------------------|-----|----------|-----------|-------|-------|-------|-------|-------|-------|-------------------|
| ECR                | 0.9 | -0.34    | 0.1       | -0.45 | 0.26  | -0.17 | 0.49  | -0.26 | -0.8  |
| PCR_{dr}           |     |          |           |       |       |       |       |       |       |                   |
| PCR_{fin}          |     |          |           |       |       |       |       |       |       |                   |
| %L CCW             | 0.52| 0.23     |           |       |       |       |       |       |       | -0.18             |
| %H CCW             | 0.47| -0.02    |           |       |       |       |       |       |       | -0.48             |
| L1 CCW             | 0.67|          |           |       |       |       |       |       |       | 0.86              |
| L2 CCW             | -0.56| -0.12   |           |       |       |       |       |       |       | 0.88              |
| L3 CCW             | -0.49|          |           |       |       |       |       |       |       | 0.81              |
| L4 CCW             | -0.46|          |           |       |       |       |       |       |       | -0.28             |
| PCR_{dr} − PCR_{fin}|     |          |           |       |       |       |       |       |       |                   |
| ECR                |     | -0.55    | 0.21      | -0.3  | -0.48 | 0.86  | 0.88  | 0.81  | -0.55 |

where $ECR$ - External cone runout;

$PCR_{dr}$ - Runout of the pitch cone after draft gearing;

$PCR_{fin}$ - Runout of the pitch cone after finishing gearing;

$L1, L2, L3, L4 (CW/CCW)$ - indicators of the relative position of the total contact patch, measured during the rotation of the gear wheel in / counterclockwise

%L, %H (CW/CCW) - dimensions of the total contact patch along the tooth and in height, measured during rotation of the gear wheel in / counterclockwise

Consider the results of the analysis for indicators of the total contact patch. The correlation coefficients between the indicators of the same name on the size of the contact patch% L, % H on the right and left side of the profile take values from 0.23 to -0.34, which indicates the absence of a correlation link. The reason for this may be different values of the deviations of the cross-sectional profile on the right and left sides of the gear tooth.

To clarify the specific causes of deviations, additional laboratory measurements are necessary on a measuring machine coordinate measuring machine, with the subsequent development of more effective methods of adjusting the machine and adjustment tools.

Since the correlation coefficients between radial beating after finishing tooth grabbing take values close to 0.5, they are closely related to the indicators of the size of the contact patch% L and% H along the right and left side of the teeth. In one of four cases, the value of the coefficient is negative, in the rest it is positive. Consequently, it is impossible to increase the size of the contact patch only by decreasing the magnitude of the radial runout.

The situation is similar for indicators of the relative location of the contact patch $L1, L2, L3, L4$. The values of the correlation coefficient are higher and in some cases reach values close to 0.9. But as for
the % L and % H indicators, they take both negative and positive values. Consequently, in this case too, a decrease in the radial runout does not lead to an unambiguous, predictable change in the location of the contact patch.

Prior to this, the results of the correlation analysis were shown between individual quality indicators, but it is possible to form new ones indirectly indicative of any processes in the technological system on their basis and consider the relationship between these indicators and part quality indicators. In this example, this indicator is the difference between the beats after the rough and the finishing gear reproduction. This difference is simultaneously related to the size of the allowance and the stiffness of the expanding mandrel. The correlation analysis data indicate the presence of an unambiguous correlation relationship between individual indicators of the size of the total contact patch and almost all indicators of its relative distance (the correlation coefficient takes values from -0.48 to -0.8 and from 0.81 to 0.88). Consequently, a decrease in this difference for most indicators of relative location will lead to an increase in the boundaries of the contact patch on the side surfaces. To do this, it is necessary to basically increase the stability of the semi-finished gear of the cogwheel by beating after the rough gear-driving operation. The data of this part of the correlation analysis confirm the conclusions of the analysis conducted by pairwise comparisons of the accuracy indicators. Similar results with slightly different values of the calculated indicators were obtained for the remaining two measured parts, therefore, the conclusions obtained are not random and are applicable to other parts processed on the considered automated transmission line.

According to the results of the analysis, a comprehensive list of corrective actions to improve the quality of the manufacture of differential satellites in circular gearing operations was developed (Table 4). From the above list, the most labor-intensive measures are related to the modernization of individual machine components. Less time-consuming actions associated with the introduction of additional transitions processing surfaces of the semi-finished gear on the machines available in the technological route of processing parts. As you can see, improving the quality of satellite manufacturing is impossible due to adjustments or sub-adjustments of the machine.

Developed corrective actions are included in the shop plan to improve the quality of products. Since their implementation requires funding, a plan for its implementation is developed for each corrective action, responsible executives and deadlines for the implementation of individual works and corrective actions are established. After they have been completed, the process of measuring and analyzing data is repeatedly performed in order to confirm the effectiveness of corrective actions.

Further, in accordance with the key quality indicators management plan, the procedure for measuring and analyzing gears is repeated at least once every 3 months.

### Table 3. Corrective actions to improve the quality of manufacture of bevel wheels

| Indicator | Method | Analysis results | Content of corrective action |
|-----------|--------|------------------|------------------------------|
| External cone runout | Primary data analysis | No grouping center | 1. Improving the stability of the internal diametral size of the base element by introducing an additional transition to fine boring or pulling. |
| | Statistical analysis | The process is conditionally stable | |
| | Control charts | There are special reasons | |
| | Correlation analysis analysis | | |
| Runout of the pitch cone after draft gearing | Primary data analysis | No grouping center | |
| | Statistical analysis | The process is conditionally stable | 2. Using another mandrel with increased rigidity. |
| | Control charts | There are special reasons | |
| | Correlation analysis of the inheritance of the beats after the draft gearing | Unambiguous inheritance | 3. Improving the stability of the external cone beats by introducing an additional transition of external turning of the external conical surface |
| Runout of the pitch cone after finishing gearing | Primary data analysis | Center of grouping | |
| | Statistical analysis | The process is stable | |
| | Correlation analysis of the hereditary relation of the beating after the finish machining and on the outer cone | There are special reasons | 4. Improving the indexing accuracy of the expansion mandrel by replacing a worn division mechanism. |
| | Correlation analysis of the inheritance | Weak hereditary | |

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of the heartbeat after finish and rough machining

Contact Spot Size Indicators

| Indicator                        | Primary data analysis   | Statistical analysis   | Control charts   |
|---------------------------------|-------------------------|------------------------|------------------|
| No grouping center              | The process is          | There are special     |                  |
|                                 | conditionally stable    | reasons                |                  |
| Correlation analysis of hereditary relations of contact patch size %L %H with a beating after finish tooth machining | Unambiguous hereditary relationships not identified |                  |

5. Additional analysis of deviations of the profile, the development of methods for adjusting the machine, the development and manufacture of adjustment tools

6. Additional analysis of deviations of the profile, the development of methods for adjusting the machine, the development and manufacture of adjustment tools

Beating difference after rough and fine gearing

| Indicator                        | Primary data analysis   | Statistical analysis   | Control charts   |
|---------------------------------|-------------------------|------------------------|------------------|
|                                 | Correlation analysis of hereditary bonds of the difference of the beats after the rough and fair gearing and parameters L1, L2, L3, L4 | Unambiguous inheritance |                  |
|                                 | Corrective actions under paragraphs 1, 2, 3 |

4. Conclusion
The results of processing the data of coordinate measurements through the consistent application of quality management methods are much more informative than their individual application. The advantage of the method is much less labor intensive compared to standard quality management methods, since there are enough measurement data of fewer parts (no less than 3), compared with their recommended number (at least 30) when performing calculations with probabilistic-statistical methods or maintenance of control charts.

As a result of the application of the technique, all groups of technological factors are identified that affect the quality of the manufacture of satellites of the differential, including hereditary ones that are not detected with the generally accepted methods of using single quality management methods.

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