Rationality and possibility of automation of precision calibration of gears

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Abstract. The main factors that determine the accuracy and quality of the ring gear during precision calibration are described. The corresponding ACS (automated control system) schemes are proposed.

Currently in the process of precision calibration of gear teeth, there are no automation elements. The operation is performed by the employee in the press, and quality control is carried out periodically, by measuring the finished product. Such a process leaves a high probability of manufacturing non-conforming products and does not allow the calibration process to be controlled.

To identify the main factors affecting the accuracy and quality of precision calibration, a matrix of significance of the system parameters \{M, W, E, T, I, S\} for cold calibration has been developed [1].

### Table 1. Significance Matrix

| System parameters M, W, E, T, I, S, E | Significance |
|-------------------------------------|--------------|
| (M) Material                        |              |
| The chemical composition of the material | +▲3          |
| Mechanical properties of the material (hardness, strength) | +▲○4        |
| Shrinkage during cooling            | -            |
| (W) Workpiece                       |              |
| The accuracy of the size of the initial semi-finished product | +○5          |
| (E) Equipment                       |              |
| The rigidity of the press           | +○3          |
| Press power                         | +▲3          |
| (T) Technological process           |              |
| Changing the workpiece temperature during the stamping process | ○1           |
| Lubrication (type)                 | ▲ 3          |
| (I) Instrument                      |              |
| Elastic deformation of the stamp    | ▲ 4          |
| Expansion of dies as a result of heating during operation | ○3           |
| Surface roughness                   | ▲ 5          |
| (S) Staff                           |              |
| Putting a semi-finished product in a stamp | ▲Δ2       |
| Lubrication of stamps (application of grease) | + Δ3         |
| (E) Environment                     |              |
Based on the ability to manage parameters, all factors are divided into: ▲ - managed proactively (at the design stage of the technology); Δ - managed by setting; ● - managed adaptively; ○ - not managed. For ranking, indicators of the target importance of process factors are used: 1-not important; 2-less important; 3-not important enough; 4-important; 5-very important [1].

According to the assessment carried out by experts in table 1[2,3], the factors that have the greatest impact on the accuracy and quality of products obtained by precision calibration are the following:
1. Precision of die tooling manufacturing;
2. Elastic deformation of the stamp;
3. Mechanical properties (strength, hardness) of semi-finished products;
4. Accuracy of the height dimensions of stamped semi-finished products before the calibration operation.

Consider the variability and control capabilities of each factor.
1. The accuracy of the die tooling is set by the designer at the design stage of the die tooling. Production of die tooling for precision calibration must be performed at high-precision machining centers with an accuracy of 0.01 mm or higher. According to the results of 3D scanning of the die tooling (figure 1), the actual profile deviation in the zone of teeth in the die tooling was less than 0.03 mm on the dies for the gear and less than 0.01 mm for the stamp of smaller dimensions for calibration of the satellite. The considered factor with high significance is managed proactively and does not require adaptive control during the stamping process.

2. Elastic deformations according to the Q-form simulation program are up to 0.05 mm in the contact spot and are critical in terms of the accuracy of the calibrated pinion contact spot. However, the ability to determine the values of elastic deformations using simulation allows you to take this factor into account at the design stage of the tooling by adjusting the geometry of the tooth profile. Therefore, this factor does not require adaptive management.

3. The mechanical characteristics of the calibrated semi-finished products depend on the chemical composition of the metal, which varies within GOST4543 [4] and heat treatment modes. During the production of a pilot batch of gears and satellites with a calibrated tooth, hardness measurements were performed after heat treatment:
   - The range of hardness for forgings made:
     - 162-187 HB for steel satellites 18ХГР;
     - 229 – 241 HB for steel satellites 25X5M.

   Taking into account the fact that the pilot stamping was made from rolled metal of one metallurgical melting, fluctuations in the chemical composition within the stamped batch can be considered insignificant. Heat treatment of forgings within the same group of forgings was carried out in one heat unit, according to a single mode. However, despite the low variability of the above factors, the spread of hardness reaches 15%. Taking into account the direct dependence on the strength, it is possible to predict a 15% variation in the deformation force during calibration.
The scatter of the values of the deformation force causes various elastic deformations of the stamp and the calibrated forging surfaces, which negatively affects the accuracy of the calibrated contact spot of the gears.

To determine the values of elastic deformations of the forging and tool depending on the strength characteristics of the hot-stamped semi-finished product, a simulation was performed in the QForm program. The modeling results are shown in Figure 2. Elastic deformation of the forging at the minimum permissible, according to the Engineering Documentation, the hardness value of 156NV is 0.132 mm; at the maximum permissible value of 207NV is 0.154 mm. Thus the difference in elastic deformations of the forging in the entire permissible range of hardness is 0.022 mm. The difference in elastic deformations of the tool is less than 0.002 mm, so they can be ignored. The dependence of the elastic deformation of the "Press-stamp" system on the deformation force is presented in the paper [5].

According to the modeling results, the total variability of elastic deformations of the forging is more than 0.02 mm. Taking into account that the tolerance to the surface of the contact spot is 0.1 mm, changing the mechanical properties of the semi-finished product makes an error of more than 20% of the tolerance field.

During the hot volumetric stamping of gear forgings, the accuracy of the obtained products is influenced by many factors, such as the accuracy of the sizes of the initial workpiece, the variability of the heating temperature of the workpieces, the accuracy of the manufacture of die tooling, etc. [6,7,8]. As a result, there is a significant variation in the height dimensions of the semi-finished products before calibration.

Figure 3 shows a histogram of the scatter in the altitude size of the batch of forgings "Satellite" obtained by experimental stamping in various conditions.

The difference between the highest and lowest values is 0.9 mm. During carrying out precision calibration, the indicated spread has a significant effect on the quality of the calibrated surface. Figure 3 shows photographs of calibrated surfaces of the forgings "Satellite" with a nominal height size of 33.5 mm and a size at the lower tolerance limit of 33.0 mm.
During calibration, equipment and tools were adjusted to the nominal size of the semi-finished product. Figure 4 (a) clearly shows the trace of the calibration tool on the surface of the teeth. In figure 4 (b), the calibrated spot was not formed over the entire required surface, and the tool footprint is uneven.

![Altitude distribution](image)

Figure 3. A histogram of altitude distribution size of the batch of forgings “Satellite” obtained during pilot stamping.

The analysis shows that the main factors affecting the accuracy and quality of calibration are the accuracy of the height dimensions and the mechanical characteristics of the hot stamped semi-finished product.

Automation of the sub-adjustment (adjustment) of the calibration press [9, 10] during operation, depending on the height dimensions and mechanical characteristics, will make it possible to solve the problem of ensuring the stability of the quality of the calibration performed.

To provide control of the calibration process, it is proposed to use the SCADA system (SCADA - Supervisory Control And Data Acquisition), which is the main and currently remains the most promising method for the automated control of complex dynamic systems (processes).

It is proposed to measure the hardness and height size of a hot stamped semi-finished product in an automatic installation consisting of the following modules:

- automated milling cutter - to prepare the surface for measuring hardness;
- automatic hardness tester (for example, model Q3000E from QNESS, Austria) – to determine the value of hardness;
- optical height meter – to determine the height value of a hot stamped semi-finished product.

The structural diagram of an automated control system for the precision calibration of gears depends on the type of press used for calibration. Figure 5 shows the structural diagram for a press with rigid kinematic connections (double-crank press). Figure 6 shows the structural diagram for a press without hard kinematic connections (hydraulic press).
The proposed automated control system of technological process is based on a three-level principle and contains lower, middle and upper levels. The upper level is an intelligent add-on in the form of a decision-making module that corrects the control of the calibration process depending on the data received from the automatic device for measuring the hardness and height of the semi-finished product. At an average level, the controller, based on the state of the monitored parameters, provides control signals to the press actuators. At the lower level, the signals of the sensors are matched with the inputs of the control device, as well as the generated commands with actuators.
The main factors that determine the accuracy and quality of the gear ring during precision calibration are described: the accuracy of manufacturing die tooling, elastic deformation of the stamp, mechanical properties of semi-finished products, the accuracy of the height dimensions of stamped semi-finished products before the calibration operation.

Structural diagrams of automated control systems for precision gear calibration are proposed, depending on the type of press used.
Figure 6. Structural diagram of an automated precision calibration process control system for a press without rigid kinematic connections (hydropress).

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