Investigation of the accuracy of gears produced by electrical discharge machining

A V Linovsky, A A Fedorov, A V Tignibidin, S V Takausk, S V Lavrentev
Omsk State Technical University, 11 Mira Ave., Omsk, 644050, Russia
E-mail: alexlinovsky@mail.ru

Abstract. The article presents the results of investigation of the small module gear wheels manufacture from steel 35 by using wire EDM on the SODICK VZ300L machine. The purpose of this investigation is to increase the accuracy of the produced gear wheels, the task of this work is studying the accuracy of gears manufactured by the control program, while the wheel contour is drawn from arcs constructed with CAD-system with a large number of reference points. Contact and non-contact methods are used to study the geometrical parameters of the produced gears. Contact measurements were carried out on the Lapik coordinate measuring machine KIM-750, contactless measurements on a tool microscope Walter UHL VMM 150. The conducted study led to the conclusion that the proposed method allows obtaining high-precision wheels and there is a tendency to enlargement this accuracy by increasing the number approximating elements in the contour construction of the produced gear wheel.

1. Introduction

Wire electrical discharge machining (WEDM) is now widely used in manufacture of parts in various industries. The ability to manufacture complex parts without a special tool is an important advantage of wire EDM, which allows the application of this machining to manufacture of gears. The absence of a special tools need makes it possible to obtain high economic efficiency of this processing method in a one-off production, as well as in the manufacture of gears with a non-standard module. And the lack of dependence of the processing capacity and mechanical characteristics in the gear wheels manufacture from the hard-to-machine materials is an important advantage.

However, WEDM has its own specific drawbacks in the manufacture of gears. One of them is that kinematics of rolling as on gear processing machines can not be realized at WEDM, therefore the tooth profile will be approximated by some number of elements in the form of segments or arcs of circles. An important point in the creation of control program models is the required number selection of approximating elements, depending on the required accuracy of the gear wheel, as well as the minimum movement of the machine drives, called the step of interpolation.

Many authors wrote about the high efficiency of WEDM application for the gears production with a small module [1]. However, it is noted the need for a thorough study of the process. The main directions in the field of EDM are described in [2] and include, among other things, the production of gear wheels by WEDM. There are also a number of studies devoted to specific problems arising in the WEDM of gears.

The authors of [3] investigated the surface integrity of the of small module wheels manufactured by the WEDM. The authors found that combinations of processing parameters with low pulse energy give higher accuracy and surface quality, microstructure, providing increased resource and performance characteristics of the produced wheels. The results show the advantage of the WEDM technology over traditional ones.
Various authors investigated the process of the required accuracy obtaining; for example, the authors [4] investigated and optimized the process of small module cylindrical gears manufacturing by WEDM. In particular, they found that the most important parameters of the process influencing the profile error and the accumulated error of the step is the pulse duration and the pause between the pulses, as well as the voltage and speed of the wire feed. The interaction between the voltage and the pause of the pulses and the pulse time with a pause of the pulses significantly affects the deviations of both accuracy parameters. The total error of the profile also significantly depends on the relationship between the pulse time and the feed rate. The main causes of deviations in the profile and pitch of the wheels are the irregular shape of the craters produced by high-energy discharges and the delay ("lag") of the wire due to the action of various forces generated at processing.

The influence of the voltage, time and the pulse pause, wire feed rate and processing speed on the total profile error and the accumulated pitch error was investigated in [5]. The authors recommend using a low voltage and short pulse time to obtain high accurate gears.

The authors [6] compared the machining of small module gears by WEDM with traditional method. They concluded that WEDM is possible to use for manufacturing small module gears. The authors studied the influence of WEDM parameters [7]. The time and the pulse pause, the wire feed speed and its tension are chosen as the input parameters, the material removal rate and the pitch error are chosen as the output parameters. The material removal rate increases and the single step error decreases with increasing pulse time. The surface was also examined, various defects were found on the surface, and the results of the energy dispersive analysis showed the presence of an electrode-tool (wire) material on the part surface.

The paper [8] investigated the obtaining of a minimum roughness at the finish by WEDM. Optimal processing parameters, selected by authors, can be used in production, including small module gears.

2. Task definition
Based on the literature review it can be concluded that the processing parameters and their influence on the output parameters have been thoroughly investigated. The accuracy can affected by the program contour, along which the control program is generated, and the accuracy of the contour, in turn, depends on the number of approximants elements from which the evolvent profile is compiled.

The task of this research is to investigate the accuracy of gears manufactured by the control program, while the contour of the wheel is drawn from arcs constructed with CAD-system with a large number of calculation points.

3. Theory
In this work the Compass Shaft 3D CAD system was used to generate wheel model. The number of calculation points is 100 (50 on the working surface and 50 on the transition curve).
With such number of calculated points the maximum deviation of the profile with the approximation is not more than 0.001 mm.
**Figure 1.** Comparison of teeth constructed with different number of calculation points

Fig. 1 presents the drawings of the gears’ teeth, constructed with approximations of 8 elements (maximum realized by the CNC machine tools) and 1000 elements, built in the CAD system Compass Shaft 3D, superimposed one on the other. The maximum deviation of the profiles is 0.004 mm. On the basis of the presented data, it was concluded that the accuracy of the gears built in the CNC system of the machine is low, and for high-precision gears, this method of construction is not suitable.

**4. Experimental results**

As a subject of research gear wheels of structural steel 35 (AISI C1035) are selected in the delivery condition with module 1. Twenty five teeth produced on the SODICK VZ300L wire-cutting machine in 4 passes (figure 2). As the dielectric fluid distilled water was used. The electrode tool was a rigid brass wire (Cu 60%, Zn 40%). The position of the nozzles is open U (half-open machining (the lower nozzle is 0.1 mm away from the part, the upper nozzle is at a distance of more than 0.1 mm from the part).

![Figure 2](image)

**Figure 2.** a) Photograph of the produced gear wheel, b) The contour of the produced gear wheel, in the CAD system Compass 3D.

The parameters of the produced gears are given in Table 1
**Table 1. Parameters of gear wheel**

| Name of parameter                      | Value of parameter |
|----------------------------------------|--------------------|
| Number of teeth                        | 25                 |
| module, mm                             | 1                  |
| Teeth angle                            | 0°0'0"             |
| Reference cylinder pressure angle      | 20°00'00"          |
| Addendum coefficient                   | 1                  |
| backlash coefficient                   | 0.25               |
| Radial coefficient of the transition curve | 0.38               |
| Tooth thickness, mm                    | 10                 |
| displacement coefficient of initial contour | 0                 |
| Degree of accuracy                     | 7-C                |
| Base diameter, mm                      | 25                 |
| Tip diameter Da, mm                    | 27                 |
| Root diameter Df, mm                   | 22.5               |
| Working pitch diameter Dw, mm          | 25                 |
| Pressure angle                         | 20°00'00"          |
| The constant chord, mm                 | 1.38705            |
| Height to constant chord, mm           | 0.74758            |
| Radius of curvature of the profile Ros, mm | 5.01328           |
| Radius of curvature of the active profile of the tooth at the lowest point, mm | 1.68524 |
| The number of teeth in the length of the common normal | 3 |
| Length of the common normal, mm       | 7.73047 -0.055 -0.125 |

The control of geometrical characteristics of the gear is made by contact and non-contact measurement methods. In the contact measurement the hexapod coordinate measuring machine of the Lapik company with the Renishaw scanning measuring head was used. When evaluating the accuracy of manufacturing gear with a non-contact measurement method the Walter UHL VMM 150 instrumental microscope was used.

The results of control of the base surfaces are shown in Table 2.

**Table 2. Results of control of the gear wheel - basic surfaces**

| Base cylinder (pin) | Diameter | Standard deviation | Cylindricity |
|---------------------|----------|--------------------|--------------|
|                     | 15.572   | 0.007              | 0.032        |
| Base plane (upper end) |          |                    |              |
| Standard deviation  | 0.002    |                    |              |
| Flatness            | 0.005    |                    |              |

The parameters of the tooth thickness along the chord, the oscillations in the length of the total normal, the radial runout of Fr, which was 0.187, the pitch deviation and other parameters are shown in Fig. 3 and in Tables 3 and 4.
a) Thickness of tooth by chord

b) Deviation of the average length of the common normal

c) Radial runout

d) The deviation of the step

e) The accumulated pitch error

f) The deviation of the pitch
Figure 3. Measured parameters. a) Tooth thickness along the chord. b) Oscillation of the total normal length. c) Radial runout. d) The deviation of the step of the left profiles. e) The accumulated pitch error of the left profiles. f) The deviation of the pitch of the right profiles. g) Accumulated pitch error of the right profiles.

Table 3. Results of control of gear wheel - parameters of teeth and length of general normal.

| Parameter                          | Value  |
|------------------------------------|--------|
| Height to chord, $h_c$             | 0.748  |
| Thickness of tooth by constant chord, $S_c$ | 1.387  |
| Average tooth thickness, $S_{cm}$  | 1.411  |
| Thickness tolerance, $E_c$         | 0.024  |
| Deviation of tooth thickness, $F_{sc}$ | 0.155  |
| Maximum tooth thickness, $S_{cmax}$ | 1.546  |
| Minimum tooth thickness, $S_{cmin}$ | 1.391  |
| Nominal length of the common normal, $W$ | 7.730  |
| Number of teeth in the length of the common normal, $z_w$ | 3      |
| Average length of the common normal, $W_m$ | 7.752  |
| Deviation of the average length of the common normal, $E_{wm}$ | 0.022  |
| Oscillation of the common normal length, $F_w$ | 0.081  |
| Maximum length of the common normal, $W_{max}$ | 7.818  |
| Minimum length of the common normal, $W_{min}$ | 7.737  |

Table 4. Results of the control of the gear wheel - pitch parameters of right and left profiles.

| Parameter                          | Value  |
|------------------------------------|--------|
| Pitch error of left profiles       |        |
| Nominal pitch, $p_t$               | 3.142  |
Upper deviation limit of pitch, +fpt 0.054
Lower deviation limit of pitch, -fpt -0.064
Pitch difference, fvpt 0.118
Nominal pitch of gearing, pb 2.952
Upper deviation limit of gearing pitch, +fpb 0.051
Lower deviation limit of gearing pitch, -fpb -0.061
Difference of gearing pitch, fvpb 0.111
Accumulated pitch error of gear wheel, Fp 0.099
Accumulated pitch error, Fpz/8 -0.003
Pitch error of right profiles
Nominal pitch, pt 3.142
Upper deviation limit of pitch, +fpt 0.060
Lower deviation limit of pitch, -fpt -0.068
Pitch difference, fvpt 0.129
Nominal pitch of gearing, pb 2.952
Upper deviation limit of gearing pitch, +fpb 0.057
Lower deviation limit of gearing pitch, -fpb -0.064
Difference of gearing pitch, fvpb 0.121
Accumulated pitch error of gear wheel, Fp 0.068
Accumulated pitch error, Fpz/8 -0.008

The cloud of points obtained on the Walter UHL VMM 150 microscope was converted into a curved line and superimposed on the modeled gear contour model according to the required standards (Fig. 4a).

**Figure 4.** a) Overlaid cloud of points. b) Contour of the teeth with 22 and 23 number.

5. The discussion of the results
During the measurement, the teeth from 22 to 25 had significant deviations from the overall picture of the contour measurement (Fig. 4b). This is due to the basing of the gear wheel on the machine during machining. Since the external gear wheel cannot be machined in more than one pass by WEDM in one installation without the use of the special turning devices, the contour was machined, with the exception of 3 teeth in four passes, and then machining was completed in one pass. In this regard, large values of deviations on 3 teeth were obtained. The use of special turning devices will avoid these errors.

The produced gear wheels correspond to the 7th degree of accuracy GOST 9178-81, with the exception of a number of teeth’s parameters 22-25. It is necessary to use another scheme of basing or
using of gear finishing. Finishing also allow to remove surface defects obtained by EDM and increase the accuracy. The using of electrochemical treatment based on static electrodynamic electrolysis is proposed.

6. Findings and conclusion
In this investigation gear wheels produced by EDM was studied. The main results are formulated as follows:

- Standard programming on the machine contains few approximating elements, the use of CAD systems is required, allowing the use of a larger number of approximating elements.
- Based on the results of the measurements, the produced wheels correspond to the 7th degree of accuracy.
- It is necessary to change scheme of basing and use special turning devices to improve accuracy.

7. References
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