Analysis of causes and mathematical description of process of manufacturing errors and local defects in mechanical system nodes

D Y Ershov, E G Zlotnikov, L E Koboyankwe

Saint-Petersburg Mining University, 2, 21st Line, St Petersburg 199106, Russia

E-mail: fetcat@mail.ru

Abstract. The article examines the main sources of technological deviations and local manufacturing defects in parts of mechanical systems. These flaws significantly affect the vibration characteristics of the system during its operation. The authors proposed a mathematical description of technological errors for further modeling and investigation of their influence on the vibration activity of a mechanical system. This allows one to evaluate the parameters of vibration processes along the symmetry axes of the rotating assembly of the mechanical system and to reveal the main places of concentration of disturbing effects in the form of dynamic reactions on the support elements and bearings.

1. Introduction
Technological errors in the manufacture of machine parts are one of the main reasons for the occurrence of vibration effects in the nodes of mechanical systems.

The technological process of manufacturing parts with high quality indicators - precision and strength - is extremely complex and difficult. To ensure sufficient quality of machine parts functioning, it is necessary to know the relative influence of individual structural elements on each other, thus, for example the influence of their mechanical properties, material properties and surface hardening methods on the accuracy of manufacturing parts. It is also necessary to have reliable methods for calculating and predicting the accuracy indexes of product quality.

2. Materials and methods. Sources of technological errors
In the technology of manufacturing components, the accuracy is characterized by many complex parameters (gears, bearings, shafts, etc.), and the operations of thermal and chemical-thermal treatment cause the greatest number of technological errors [1, 2].

The main sources of such errors are:
1. unequal absolute change in linear dimensions and the volume of different parts of the part during thermal expansion (compression) due to different sizes and masses of the conjugate elements of the part;
2. insufficient rigidity of the part, resulting in deflections under the action of its own gravity in the process of heating during carburization and hardening;
3. phase transformations:
   - change in the specific volume of the core components;
   - change in the specific volume of the component’s surface layer;
- manifestation of anomalously high reversible plasticity of the material;
- change in the depth and volume of the cemented layer on surfaces of different curvatures;
4. errors in the dimensions and shape of components after machining and before hardening.

In the practice of heat treatment, errors in the components are divided into two types [1, 2]:
1. Errors caused by a change in the specific volume of steel, during phase transformations, leading mainly to a change in the dimensions of the part with an approximate preservation of the geometric shape similarity before and after heat treatment;
2. Errors caused by thermal and structural stresses, which leads to distortion of the shape of the surfaces, curvature of rectilinear axes, relative displacement of individual parts of the component, uneven changes in linear dimensions.

All this leads to a change in diametrical and axial dimensions, as well as to the component’s shape distortion. Errors in the dimensions and shape of components after machining are added together with the above-mentioned errors. Certain portions from the total error are contributed by dimension errors, arising from the stress state of the metal before hardening. This kind of metal condition is highly affected by the types, modes of machining and pre-heat treatment of the metal [3].

A significant contribution to the total dimensional error and component shape is added by separate operations of chemical-thermal hardening. This leads to dimensional instability after hardening. Therefore, in order to ensure the required accuracy of the dimensions and shape of the components, it is necessary to choose such regime of chemical-thermal hardening, which provides the required strength parameters without normalization. With stepwise hardening without normalization, error is approximately 1.5 times lesser [1, 2, 4].

Impacts on the workpiece during the process of hardening render the chemical composition and physical state of the metal [2]. For example, as the carbon content increases, the volume of the metal increases after quenching. The different content of alloying elements in steel, leads to a change in the shape (warpage) of the workpiece. The errors in the shape and dimensions of the part during machining are added together with the errors caused by the hardening. In this case, the residual stresses renders a significant effect. In some cases, the shape errors are caused by the heating of the workpiece with increased residual stresses, shape errors, caused by heating parts with increased residual stresses, increases almost 2 times compared to the corresponding errors measured before heating [4].

The causes of occurrence and development of local defects in the nodes of mechanical systems are discrete inclusions - impacts caused by different nature, namely:
- concentration of vibration effects from unbalance of rotating masses;
- various combinations of unevenness of the contacting surfaces of the nodes of the mechanical system, and of harmonic character;
- violation of the technological process of manufacturing parts of mechanical systems.

A defect occupying an insignificant part of the surface of a product is called a local one. It has a discrete structure and is manifested in the information vibroacoustic signal as a form of periodically repeated pulses of short duration [5, 6].

Figure 1 shows images of local defects.

![Image](image_url)

**Figure 1.** Types of local defects in nodes of mechanical systems: a - ship liner; B - motor-anchor unit
When the controlled unit of the mechanical system is operated, it is possible to determine the various phases of the formation of unevennesses of the contacting surfaces. The first phase corresponds to the generation of local defects in the places of action large values of the vibrational action. The second phase corresponds to the preservation of local defects and the development of their shape and size.

The conditions for the formation of local defects are of random nature, but from the moment of the origin of the defect, the process of formation and development has a quasi-periodic character. Therefore, a Fourier analysis is used for its mathematical description [6-8].

3. Mathematical description of technological errors

One of the most important technological factors, most significantly affecting the quality indicators during the manufacturing of components such as bodies of revolution under various production conditions, is the error of basing on various operations for the technological process. The components must be oriented in a certain way with respect to the coordinates of the machine and the cutting tool. When basing the workpiece on each technological operation, it is necessary to prevent the formation of new errors, convert existing errors and to reduce the errors that have arisen in previous operations.

The error in the shape of the cylindrical component is determined by the magnitude of the deviation from the nominal, from which quality of the basic circle is obtained.

The magnitude of the deviation from roundness is determined by the position of this circle. For completely identical surfaces, deviations from roundness are estimated by values that differ from each other by 10-15% or more. There is a technique for determining the deviation from roundness, in which the base, average circumference is determined relative to the real profile by the method of least squares [9]:

\[ \Delta = \sum_{i=1}^{n} (r_i - r_0)^2 = \text{min.} \]  

Radius of the middle circumference \( r_0 \) is defined as the average value of the current radii \( r_i \) real profile, measured in \( n \) dots:

\[ r = \frac{1}{2\pi} \int_{0}^{2\pi} r \varphi d\varphi \quad \text{or} \quad r_0 = \frac{1}{n} \sum_{i=1}^{n} r_i, \]  

where \( \varphi \) – argument of the function.

The average circumference as a base for counting the deviation of the shape allows one to obtain the most unambiguous and reliable results. The coordinates of the centre of the middle circumference change even with insignificant changes in the real profile, with respect to which it is carried out. With a decrease in the shape error of the profile to zero, it coincides with the middle circumference.

Deviations of the shape and position of the surfaces of revolution constitute a radial runout. The real profile of the surface of revolution in the cross section when the radial runout is varied can be represented as a periodic function with a period \( 2\pi \), continuous and corresponding to the Dirichlet criterion. An empirical periodic function determined by the radial runout graph for any fixed value of the argument can be represented as a trigonometric polynomial of the Fourier series [9, 10]:

\[ f(\varphi) = \frac{a_0}{2} + \sum_{k=1}^{\infty} (a_k \cos k\varphi + b_k \sin k\varphi), \]  

where \( \frac{a_0}{2} \) - constant member of the series; \( a_k, b_k \) are the coefficients of the Fourier series; \( \varphi \) - discrete values of the angle of rotation of the part when measured; \( k \) is the number of the harmonic.

Since the radial run-out graph of the technological base is a function defined by particular discrete values, Bessel’s formulas are used to determine the characteristics of the series:

\[ a_k = \frac{2}{N} \sum_{i=1}^{N} \Delta_N \cos k\varphi; \quad b_k = \frac{2}{N} \sum_{i=1}^{N} \Delta_N \sin k\varphi; \quad a_0 = \frac{2}{N} \sum_{i=1}^{N} \Delta_N; \]
\[ A_k = \sqrt{a_k^2 + b_k^2}; \quad \tan \alpha_k = \frac{b_k}{a_k}, \quad (4) \]

where \( N \) - number of measurements; \( A_k \) - amplitude of the corresponding harmonic; \( a_k \) - phase angle; \( \Delta_N \) - the instrument reading during the measurement.

The amplitude and phase of the first harmonic (\( k = 1 \)) determine the magnitude and angular position of the eccentricity of the axis of rotation in polar coordinates when measured. The combination of harmonics of the second and subsequent higher orders reflects the character of the shape change within the middle circumference, and allows determining its numerical value.

When analyzing the form of the technological base, it is most expedient to apply a dependence allowing directly excluding the eccentricity from the radial runout graph:

\[ \Delta_E = \Delta_N - e_{TF} \left[ \cos(\alpha - \varphi) + 1 \right], \quad (5) \]

where \( \Delta_E \) - actual error values in the form of technological error for the technological base shape at each measured point; \( e_{TF} = A_1 \) - eccentricity determined by expanding the empirical function into a Fourier series; \( \alpha \) - angle of eccentricity direction; \( \varphi \) - angle of the rotation variable value of the workpiece when measuring the radial runout. The position of the middle circumference relative to the real profile is determined according to the expressions (4).

4. Conclusion

At the nodes of mechanical systems, during their production, technological errors with a local structure are formed, without affecting the service life of the product, and create concentrations of vibration effects, which serve as conditions for the subsequent formation of local defects [5, 7].

The error setting and periodic failures of technological equipment that is completely in the production cannot be excluded. Equipment failures and operator errors at a certain time may be at the value of the total tuning error [11].

Adjustment errors, for example, can lead to increased cutting forces during machining of the workpiece. As a result, an additional dynamic load acting on the workpiece is created. With this increase in the allowable value, deformation of the surface layer of the workpiece material occurs, and structures having an unequal volume are formed. With a further increase in concentration density of vibration effects, this circumstance can lead to the formation of slightly discernible shells and dents on the surfaces of the parts. Deformation of the surface layer leads to the appearance of residual stresses in the surface layers of the material, which disappear after the assembly of the product in the absence of any external loads. Internal stresses also arise due to casting shrinkage, uneven plastic deformation, heat treatment and the machining of the workpiece. Outwardly, these strains do not appear in any way, the detail can be strained almost to the boundaries of destruction, but by appearance, it does not differ from the workpiece that is free from internal stresses [12].

It is practically impossible to produce parts with perfectly smooth surfaces and, thus, even under the smallest loads on individual microroughnesses of the surface, stresses always arise, leading to plastic deformations. The stress concentration, when the permissible voltage is exceeded, creates conditions for the formation of local defects.

Thus, technological errors in the manufacture and assembly of nodes of mechanical systems, as well as contact voltages, arising when performing various operations of the technological process of manufacturing system components, are very significant factors together with studying and creating certain methods for diagnosing them at the design stage of the mechanical systems and before putting them into operation.

References

[1] Skeeba VYu, Ivancivsky VV, Kutyshkin A V and Parts K A 2016 IOP Conf. Series: Earth and Environmental Science 126 012016
[2] Travieso_Rodrigues J A, Gras G G, Peiro J J, Carrillo F, Dessein G, Alexis J and Rojas H G 2015 Materials and Manufacturing Processes 30(12) 1490-97
[3] Olt J, Madissoo M, Maksarov V V 2011 *IEEE Int. Symp. on Assembly and Manufacturing (ISAM 2011)* 12-17

[4] Krasnyy V, Maksarov V and Olt J 2016 *Annals of DAAAM and Proc. of the Int.DAAAM Symp.* 151-156

[5] Balitsky F Y, Sokolova A G, Dolaberidze G V, Ivanova M A 2013 Diagnostics of machine defects in nonlinear vibrodiagnostics using the method of cascade vibration demodulation / *Vestnik of Scientific and Technical Development* 12 (76) 3-12

[6] Tony L. Schmitz and Kevin S. Smith 2009 *Machining Dynamics Frequency Response to Improved Productivity* (Springer Science+Business Media LLC) p 310

[7] Bernard F and Gaffet E 2001 *Int. J. Self-Propag. High-Temp. Synth.* 10(2) 109–132

[8] Travieso Rodrigues J A, Gras G G, Peiro J J, Carrillo F, Dessein G, Alexis J and Rojas H.G. 2015 *Materials and Manufacturing Processes* 30(12) 1490-97

[9] Yawlenksy A K, Belousov A A, Melnikov A A, Sevastianov A A and Chavoronkov K A 2007 Vibrodiagnostic of work machines *VDI Berichte* (2002) 513-520

[10] Sokolova A G and Balitsky F Y 2012 9th International Conference on Condition Monitoring and Machinery Failure Prevention Technologies 2012, CM 2012 and MFPT 2012 2 932-942

[11] Ivashutenko A S, Martyushev N V, Vidayev I G, Kostikov K S 2014 Influence of technological factors on structure and properties of Alumina-Zirconia ceramics *Advanced Materials Research* 1040 845-849

[12] Ardashkin I B, Yakovlev A N, Martyushev N V 2014 Evaluation of the resource efficiency of foundry technologies: Methodological aspect *Advanced Materials Research* 1040 912-916