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Verification methods for micro gears. Analysis of double flank roll testing applied to micro gears

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Abstract

In recent years there has been a considerable interest in microsystems, named as MEMS (Micro Electromechanical Systems), which are present in daily life by means of different products coming from several sectors as automotion, medical or consumer. Its continuing expansion is expected, derived from the trend towards miniaturization of components and the increasing applications for these micro devices. To overcome this, the technology to produce these products known as microsystem technology (MST), has been improving in order to allow the manufacturing of this type of parts becoming of growing importance over the past years. Micro gears are commonly used in electronics industry where the miniaturization process follows a constant evolution with multiple use advantages despite their small size. In this work the study and analysis of the existing verification techniques for micro gears together with the definition of a double flank rolling test focused on these gears is presented.

Keywords: micro gear; double flank roll testing; MEMS

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1. Introduction

A broad range of verification techniques for gears are currently available in the market but not so many seem to be valid or extrapolated for a micro range. Thus a thorough analysis of these techniques and a definition of a double flank rolling test for micro gears was accomplished in this paper.

The first task to be carried out was the analysis of the different types of existing gears focusing the current work only on cylindrical gears due to its broad application in the micro range.

A research on verification techniques for micro gears currently available in the market was accomplished, covering a complete range by Goch et al. (2003) from tactile to optical measurement including manual and automatic measuring instruments, specific tests for verifying the correct and accurate rolling performance of the gear, like single or double flank roll testing, or computed tomography.

Despite the wide expansion of double flank roll testers as reliable verification method for gears, for the time being, there are no commercial solutions of double flank roll testing machines for micro gears, being the feasibility analysis of this verification technique one of the key points in this work.

The dimensional definition of the micro gears to be verified in the study was crucial, generating thereby the physical dimensions required for the double flank roll tester to be designed. An example of a micro gear could be seen in Figure 1.
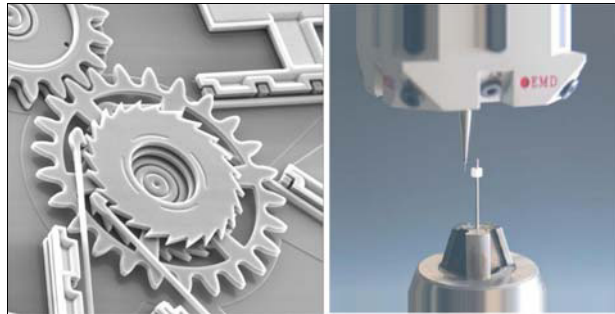

Figure 1. Micro gears image captured by Surface Scanning Microscope.

Here was generated the first design of the double flank roll tester machine for micro gears with pitch diameter from 1 to 10mm and radial composite deviation tolerances according to norm ISO1328-2 and DIN3963. Based on this first design, where the main functional blocks of the machine were described and defined, the measuring systems and components needed were preselected taking into account the dimensional and accuracy requirements.

2. Testing requirements analysis

In this work was generated the first design of the double flank roll tester machine for micro gears inspection, defining the main machine functional blocks, selecting the appropriate measuring systems and components, taking into account the dimensional and accuracy requirements of the system and defining the corresponding radial composite deviation tolerances according to norm ISO1328-2 and DIN3963. The main problem faced for tolerances definition was that in the mentioned standards there was no tolerance value for such a small gears dimension. According to norm ISO1328-2, the minimum normal module with existing and defined tolerances is 0.2. In this case, the main parameters of the test gear (micro gear) are the following:

Table 1. Definition of gear parameters.

	Gear parameters
Normal module (m)	0.1
Pitch diameter (d)	1.3mm
Number of teeth (z)	13
Accuracy grade	5

For the radial composite inspection, the test gear and a master gear of higher accuracy grade are rolled against each other without backlash being both meshed at a centre distance lower than the nominal. A force acting in the radial direction ensures that left- and right-hand flanks of the gears always remain in simultaneous contact.

As a result, the curve of centre distance variations a" within one revolution of the test gear is generated, determining on this way the accuracy grade of the test gear (Figure 2).
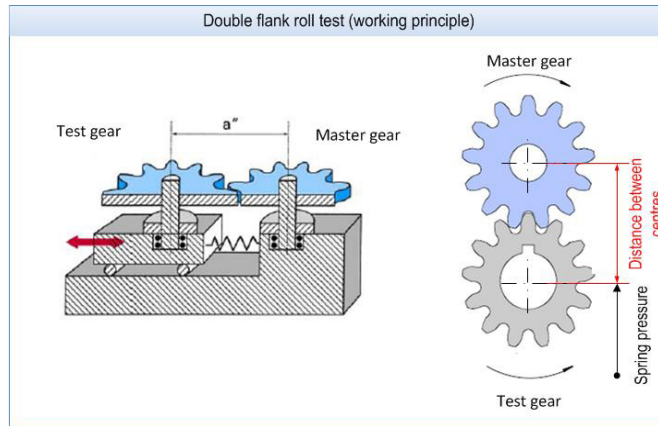

Figure 2. Double flank roll test principles. Source Frenco GmbH

Out of this measurement process, the radial composite deviation parameters Fi", fi" and Fr''which show the accuracy of the micro gear, could be obtained (Figure 3).

- Double flank rolling deviation Fi": Fi" is the difference between the maximum and minimum values of the working centre distance, a", which occurs during a radial (double flank) composite test, when the product gear with its right and left flank simultaneously in tight mesh contact with those of a master gear, is rotated through one complete revolution. (DIN3960/3963)
- Double flank rolling tooth-to-tooth deviation fi": fi'' is the maximum value of the radial composite deviation corresponding to one pitch, $360°/z$, during one complete cycle of engagement of all the product gear teeth. (DIN3960/3963)
- Radial Runout Fr'': the value of radial runout of the gear is the difference between the maximum and the minimum radial distance from the gear axis as observed by removing the short-term or undulation pitch deviations and analysing the long-term sinusoidal wave form.
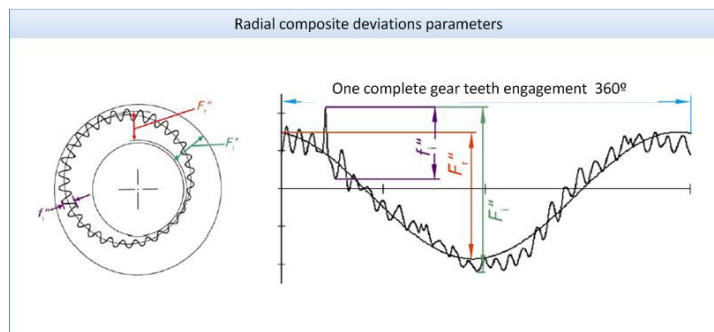

Figure 3: Radial composite deviations diagram

The maximum tolerance values for the radial composite deviations **Fi", fi"** and **Fr"** are defined within the norm ISO1328-2 depending on the normal module m, pitch diameter d and accuracy grade Q of the test gear.

The radial composite accuracy system comprises nine accuracy grades of which grade 4 is the highest and grade

12 is the lowest.

The tolerance values given in the norm are calculated and used for accuracy grade 5. Therefore, the corresponding values for higher or lower accuracy grades are obtained multiplying or dividing by $2^{0.5}$. A radial composite deviation tolerance for a defined accuracy grade Q could be obtained multiplying the given value for accuracy grade 5 by $2^{0.5(Q-5)}$.

In this work, due to the small normal module m=0.1 of the test gear, there are no radial composite deviation tolerances available in ISO1328-2 due to the fact that the minimum normal module m available is 0.2. To obtain the maximum tolerance values for Fi", fi" y Fr", following formulae from ISO1328-2 could be used for accuracy grade 5 given the normal module m and pitch diameter d (mm) of the test gear.

$$Fi"=3.2m + 1.01\sqrt{d} + 6.4$$

$$fi"=2.96m + 0.01\sqrt{d} + 0.8$$

$$Fr"=0.24m + 1.0\sqrt{d} + 5.6$$

On these grounds, the maximum tolerance values for radial composite deviations Fi", fi", Fr" of the micro gear to be inspected considering accuracy grade 5 are shown in Table 2. Likewise the maximum tolerance values for the accuracy grades 12 and 4 could be calculated and will give a reference value for the measuring components selection to be included in the double flank roll tester.

Table 2. Test maximum values for radial composite deviations Fi", fi" and Fr".

	Test gear Accuracy grade 5 d = 1.3mm	Test gear Accuracy grade 12 d = 10mm	Test gear Accuracy grade 4 d = 1mm
Fi" (μm)	7.8715	112.1630	5.4659
fi" (μm)	1.1074	12.7576	0.7821
Fr" (μm)	6.7642	99.4054	4.6839

3. Double flank roll tester model

Due to the lack of existing commercial models for double flank roll testers applied to micro gears verification, a functional blocks design of the machine adapted to the selected micro gear dimensions (Table 1) is accomplished in this work.

One problem faced in the model realization was the selection of the master gear to be used in the roll test. Both normal modules for micro gear and master gear should be equal, m=0.1 and given this value the pitch diameter d and number of teeth z for the master gear could be defined.

As no commercial master gear with pitch diameter d =1.3mm was found, it was decided to increase the master gear diameter to d=30mm resulting in a teeth number z=300 (Table 3).

Table 3. Definition of micro gear and master gear parameters.

	Micro gear parameters	Master gear parameters
Normal module (m)	0.1	0.1
Pitch diameter (d)	1.3mm	30mm
Number of teeth (z)	13	300
Accuracy grade	5	A (2)

According to DIN3970, the master accuracy grade needed for the inspection of a micro gear with accuracy grade 5 according to ISO1328-Part 2 is accuracy grade A.

In order to generate the first tester model, it is necessary to define the main tester dimensions which will be derived from the dimensional range of the micro gears to be inspected. In this case the pitch diameter d of the micro gear is 1.3mm and based on this dimension, it is fixed an admissible gear diameter range of the tester which will determine the final roll tester constructive dimensions.

Table 4. Definition of pitch diameter range.

	Test gear parameters
Pitch diameter *(d)*	1.3mm
Maximum pitch diameter *(d$_{max}$)*	10mm
Minimum pitch diameter *(d$_{min}$)*	1mm

Based on the maximum tolerance values for radial composite deviations parameters Fi", fi" and Fr" shown in Table 2, the maximum tolerance value of the double flank rolling tooth-to-tooth deviation fi" for accuracy grade 4 (best accuracy) and lowest gear diameter (Table 4, d=1mm), will determine the minimum measuring equipment resolution required. The value of the double flank rolling deviation *F*i" for accuracy grade 12 (worst accuracy) and higher gear diameter to be inspected in the tester (Table 4, d=10mm) will decide the maximum measuring range available for the double flank roll tester.

Both values will serve for the selection of the measuring components to be installed in the double flank roll tester, assuming a restrictive components selection in terms of resolution and the widest possible in terms of measurement range.

- Range of measurement: 135 μm
- Minimum equipment resolution: 0.01 μm.

Once the main metrology requirements of the double flank roll tester are decided, the next step is the definition of the basic functional blocks the equipment will be composed of and the selection of its main components.

The tester model designed in this work is similar to a standard gear double flank tester but with the peculiarity of the need to adapt the tester to a micro measurement range (Table 4) and the high equipment resolution required. This fact will imply the selection of high precision components and the specific design of the mechanical fixations for the micro gear to be inspected.

4. Double flank roll tester functional blocks definition.

The main functional blocks that will integrate the future double flank roll tester are the following:

a) Steel base or path
Fixed mechanized steel path where the two gear carriages are settled. The fixed carriage will remain still allowing only the swing movement of the flexible mechanism. The mobile carriage that holds the master gear rolling against the test gear, could slide along the path in the X direction till reaching the nominal position between gear centres.

b) Fixed carriage
Steel carriage which holds the test gear. It will integrate several parts as the fixing system for the micro gear, the pressure system which will assure the tooth contact without backlash among both gears teeth once the nominal centres position is reached, and a capacitive sensor.

c) Gear to be inspected or test gear
Micro gear with the dimensions explained in Table 1.

d) Fixing system
The fixing system is a fixture that assures the right position of the micro gear along the test. The main difficulty is derived from the small gear diameter, d=1.3mm. Hence, it is decided to use an axis fixing the micro gear in the inner gear diameter. This axis will be placed on the fixed carriage and will allow the loose turn of the gear during the test.

e) Capacitive sensor
The register of the centre distance variation a" within one revolution of the test gear is made by a capacitive sensor. This sensor will evaluate the distance between the probe and the target by capacitance measurement.

The minimum resolution required for the sensor is 0.01μm and will have a measuring range of 135 μm according to the calculated tolerance values of Fi", fi" and Fr" (Table 2).

A capacitive sensor from supplier *Lion Precision* was selected, choosing the probe, target and controller model

shown in Table 5, Figure 4 and Figure 5.

Table 5. Capacitive sensor parameters (Source Lion Precision)

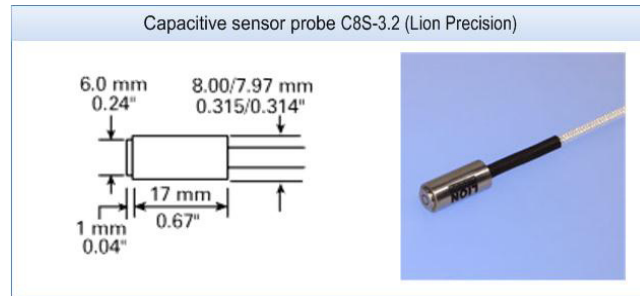| Sensing area diameter (mm)	Probe model	Range (µm)	Near Gap (µm)	Resolution (nm)	Controller model
3.2	C8S-3.2	500	250	7	CPL190

Figure 4. Capacitive sensor probe (Source Lion Precision)

Figure 5. Capacitive sensor controller (Source Lion Precision)

f)   Flexible fixture

The fixed carriage will have a flexible fixture with a blocking position determining the zero position of the tester. The non-blocking position of the flexible fixture will assure continuously the contact between both gear flanks along the roll test. A spring parallelogram is considered to be included. Due to the small size of the gear, the force to be transmitted during the test should be very low in order to avoid any damage in the micro gear. The probing force depends on the test gear size and will oscillate initially between 30N and 100N according to Kleis et al. (2003).

Taking into account the low probing force, this flexible fixture will have two main functions. On one hand, it avoids any backlash between the test gear and the capacitive measuring system which registers the gear centre movement. Due to the accuracy required, it is extremely important to avoid this backlash in the swing movement kinematic chain. On the other hand, working always on the linear movement area, the flexible fixture acts as a linear carriage to allow the swing movement and as a system which assures the contact between the gears flank, due to an existing force against the movement in any carriage position. In the flexible fixture design should be

considered that the fixture must be able to maintain itself in the linear area generating the necessary force to assure the contact and guarantee its correct working.

g)   Mobile carriage
  In this mechanized steel carriage the mater gear is positioned by means of a fixture.

h)   Master gear
  Gear which will be rolling against the micro gear to be inspected in the roll test. The master gear parameters are shown in Table 3.

i)   Servomotor
  The master gear rotary movement is actuated and controlled by a servomotor. In this application a DC motor model Series 1717-024 SR (Figure 6) from supplier Faulhaber GmbH is selected. The motor has a diameter of 17mm and a total length of 26.1mm, enabling these dimensions an easy integration into the roll tester and giving a maximum torque of 2mNm initially enough to actuate the master and test gears.
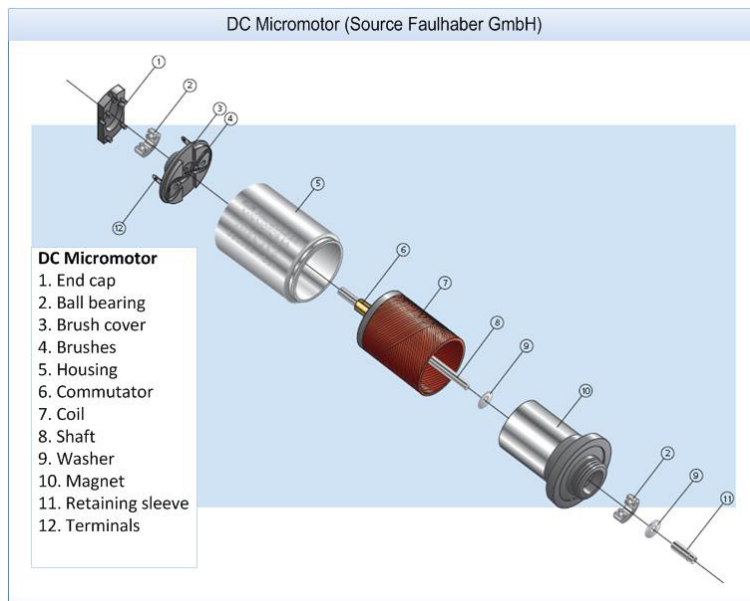

Figure 6. DC Micromotor (Source Faulhaber GmbH)

j)   Pressure system
  The adjustment of the fixed carriage position to the nominal distance between gear centres could be manually made by a hand wheel and a screw according to the measurement of a laser encoder integrated into the mobile carriage.

k)   Laser encoder
  The distance measurement along the X axis is made by a laser encoder. This measurement is used to settle the position of the master gear along the test (nominal distance between gear centres). An optic fibre HeNe laser encoder model RLE (Figure 7) from supplier Renishaw composed of a laser unit of one axis RLU and a detector head RLD10 with nanometric resolution will be placed into the mobile carriage and the path respectively. In order to avoid Abbe error the position of the laser encoder should allow the measurement in the same movement direction of the system. The resolution of the laser encoder equipment is 10nm.

Figure 7. Laser encoder unit RLU10 (Source Renishaw)

4.1. Double flank roll tester 2D model for micro gear inspection

In the Figure 8 is illustrated the 2D model for the double flank roll tester with a simple scheme of the main functional blocks previously listed below.
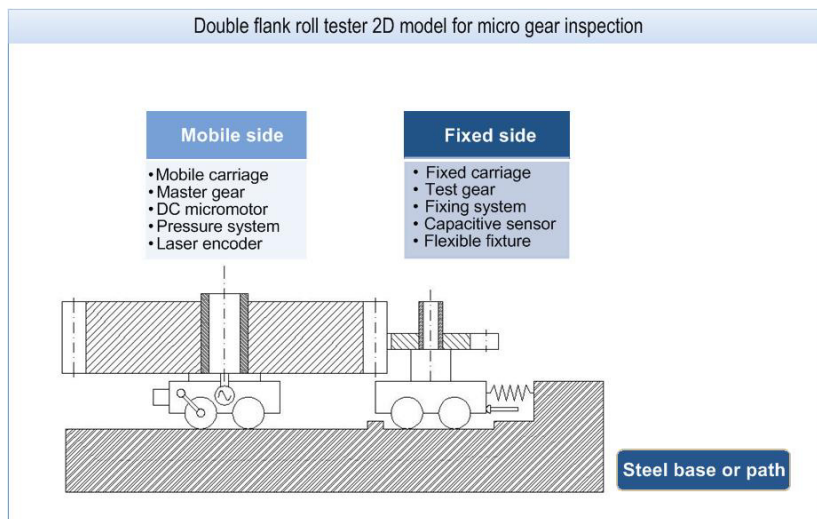

Figure 8. Double flank roll tester 2D model for micro gear testing

5. Conclusions

Considering the findings and research done in this study, it is concluded as feasible the use of the double flank roll testing as verification technique for micro gears. The final design of the tester shows big challenges due to the micro gear dimension and the measurement resolution required, which implies a complex mechanical design of the gears and the flexible fixtures. It is important to point out that the micro gear should not be damaged during the test and this will depend on the perfect fit of the installation to the dimensional range required.

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