Precise Injection Moulding of Polymer Gears

Luka ROBLEK, Jože TAVČAR

Abstract: Plastic gears are indispensable in the production of mechatronic components and small household appliances due to cost-effective manufacturing, good tribological properties and other favourable characteristics. However, the shrinkage of polymers during injection moulding affects important gear characteristics, such as tooth profile, gear diameter and runout. Gear tooth errors can cause intensive wear, overheating, or even gear pair dysfunction. In mechatronic devices for positioning systems, uniform meshing of a gear pair is a key characteristic. Double flank roll checker is used for gear quality verification. This paper deals with the improvements of the injection moulding process and reducing the double flank runout error of the involute spur gears. The gear measurement systems analysis was done first. Optimal moulding parameters were determined by using design of experiments. The moulding tool modification has significantly contributed to the reduction of double flank runout error.

Keywords: Polymer gears, injection moulding, design of experiments, moulding tools, gear shape correction

1 Introduction

The main purpose of gear pairs is the transfer and modification of torque and velocity without sliding. To meet the fundamental law of gearing, gear teeth must have an accurate tooth profile. In general, injection moulded plastic gears are of lower quality compared to metal gears due to shrinkage.

Modern moulding machines with advanced process controls enable the keeping of the mould temperature, injection pressure and other variables within a tight window [1]. However, precise injection moulding of polymer gears demands more than just a modern machine. It involves specialized measuring equipment, appropriate tool design and qualified operators.

The paper presents a systematic procedure of improving the moulding process and reducing the double flank runout error of the polymer gears which is a characteristic of gear quality that results in an effective centre distance variation. The analyses of gear measuring methods were done and the optimal moulding parameters were defined by using the *design of experiments* method. Based on the measurement results and flow simulation, the moulding tool design was modified to ensure constant moulding conditions. A computer program was developed to analyse the double flank runout error and to attain the ideal teeth shape based on that error.

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2 Measurement system analysis

The Measurement System Analysis (MSA) was applied to identify the influences of the measuring equipment and operators on the measurement. The equipment and operator variation are implied in the GR&R (Gage Repeatability and Reproducibility) variation which defines the proportion of the measurement error in relation to tolerance or process variation. Factor %GR&R is the proportion of the GR&R variation and total process variation. The gauge is capable when %GR&R value is less than 10 % and conditionally capable when %GR&R is between 10 % and 30 % [2].

The measured plastic gear has its geometry determined by the characteristics shown in *Table 1*.

Table 1. *Characteristics of measured plastic gear*

Pressure angle α [°]	20
Number of teeth z [ ]	40
Module m [ ]	0.5
Profile shift coefficient x [ ]	0.0068

2.1 Double flank runout

Double flank inspection is a useful tool to determine the general quality of a gear, including size, runout and tooth-to-tooth rolling action. The measured gear is rolled in a tight double flank contact with a master gear. No backlash is provided, as the gear is spring-loaded against the master gear on the inspection machine (*Figure 1*). The centre distance of gears is meas-

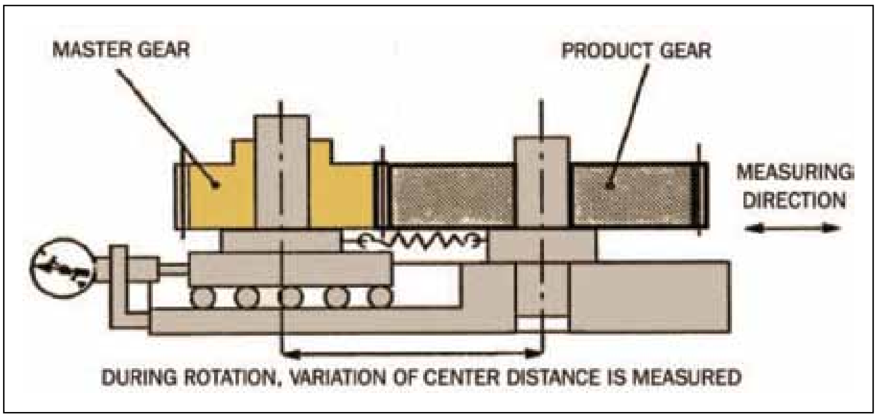

Figure 1. *Schematic concept of gear rolling device. [3]*

ured during rolling and it yields the "tooth-to-tooth" and the "total composite" errors. The double flank runout (hereinafter just runout) can also be calculated on computer driven gauges [3].

The MSA was done with the statistical program Minitab. The gauge is conditionally capable, with the %GR&R factor of 12.12 %.

2.2 Base Tangent Length

Base Tangent Length (*Wk*) is the simplest and the most widely used method for determining gear tooth thickness by measuring the length across a certain number of teeth (*k*). To avoid tooth deformation of plastic gears during the measurement, a low-force micrometer must be used.

The MSA showed that the gauge is not capable if measuring is conducted by holding the micrometer and the gear in our hands. The %GR&R factor was nearly 30 %. The main cause was repeatability, which means the measuring itself was faulty. An improvement of the measurement process was achieved by mounting the micrometer in a special holder and by holding the gear in our hands. The %GR&R factor was reduced to 5.4 %.

2.3 Measurement over pins or balls

This is an indirect measurement of the gear tooth thickness over two measuring bodies, which are inserted between the two most distant gear teeth. For each gear, the adequate diameter of measuring ball or pin must be selected and the corresponding distance over pins or balls must be calculated. A low-force micrometer is also needed for this measurement. The gear should be mounted in a holder in order to get the GR&R result under 15 %.

3 Optimisation of moulding parameters

The injection moulding process includes the plastification, injection, packing, cooling and part ejection stages. During the plastification stage, the polymer melt is plasticized from solid granules. During the filling stage, the polymer melt is forced from the barrel of the moulding machine into the mould. After the mould cavity is filled with the polymer melt, the packing stage provides additional material into the mould as the molten plastic cools and contracts [4].

The moulding process is therefore very complex, affected by several parameters, such as melt temperature, filling time, filling pressure, packing pressure, cooling time, mould temperature, and many others. Approximate values of these parameters can be found in polymer data sheets; however, for precise injection moulding, they should be determined by systematic experiments.

3.1 Design of Experiments

Design of Experiments (DoE) is a method used for a systematic analysis of the impact of the technological parameters and their interactions. The first step is to determine the goal functions, which in our case were the gear runout and the base tangent length. The second step is to determine all the influential parameters and to select the control parameters and their levels [5].

Based on the recommendations of Steinko [6] and from our technologist's experience, mould temperature, volumetric flow rate of filling, and packing pressure should be chosen as control parameters for the experiment in order to attain minimal shrinkage and warpage of a moulded part. Only two levels were chosen at first, in order to assess the influence of those parameters on runout. A full factorial design was chosen, so there were eight runs. The selected values of the parameters are shown in *Table 2.*

3.2 Experimental results

The DoE analysis was done in the statistical programme Minitab. The influences of all three parameters on runout and their interactions were analysed first. The programme calculates the main effect for every single influence. The influence of a parameter or the interaction of parameters can be excluded for further analysis if the main effect is

Table 2. *Selected parameters and their levels for DoE.*

Parameter	Level 1	Level 2
Mould temperature [°C]	133	153
Volumetric flow rate of filling [cm^3/s]	2.8	5.3
Packing pressure [MPa]	100	140

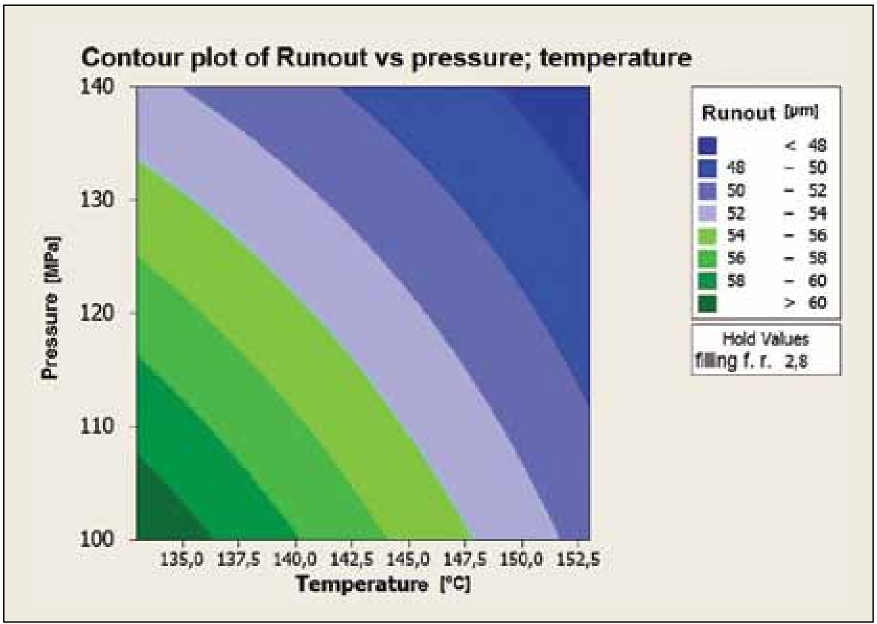

Figure 2. *Influence parameters of runout in contour plot.*

greater than 0.05 [2]. It turned out that many of them can be disregarded. According to the analysis, the runout is mainly influenced by the packing pressure, mould temperature, and their interaction. The results of the mentioned influences are graphically shown on the contour plot in *Figure 2*.

The base tangent length analysis gave very similar results to the runout analysis since the same parameters have an important influence. The contour plot of the base tangent length analysis is shown in *Figure 3*. Regarding the results of the DoE analysis, it can be concluded that the influential parameters are *packing pressure* and *mould temperature* and that the optimum values are 140 MPa and 153 °C. However, it is possible to reduce the runout error only up to 10 % with the optimisation.

4 Injection mould optimisations

An injection mould is a complex system that must meet many demands imposed by the injection moulding process. The primary functions of the mould are giving the part the proper shape, an efficient transfer of heat from the hot polymer, and the ejection of the part from the mould [4].

4.1 Mould modifications

The injection mould of the discussed gear was a prototype and therefore some modifications were required. The main goals of the optimisation were the stabilisation of the moulding process and the reduction of the runout error.

The feed system consists of a hot runner and an ordinary primary runner which is divided into three secondary runners *(Figure 4)*. The feed system was modified based on the polymer flow simulation made in SolidWorks Plastics with the optimal moulding parameters from the DoE analysis. It was shown in the simulation that secondary runners are not filled at the same time, as it can be seen on Figure 4. The filling simulation was paused at the point where melt front in one of the secondary runners reached the cavity. The primary runner was then modified in order to get an even filling. It turned out that only a small modification of the separation area was needed to get an even gear filling *(Figure 5)*.

The cooling system was redesigned. The prototype mould had electric heaters which heated up the entire mould to the working temperature. However, during the process, no cooling was provided. Therefore, liquid cooling was added to stabilise the temperature. Because of the limited space, the cooling lines were added only on both sides of the cavities.

The venting system was also part of the mould improvements. Vent channels were provided across the insert on the parting plane and clearance was ensured around the ejector pins.

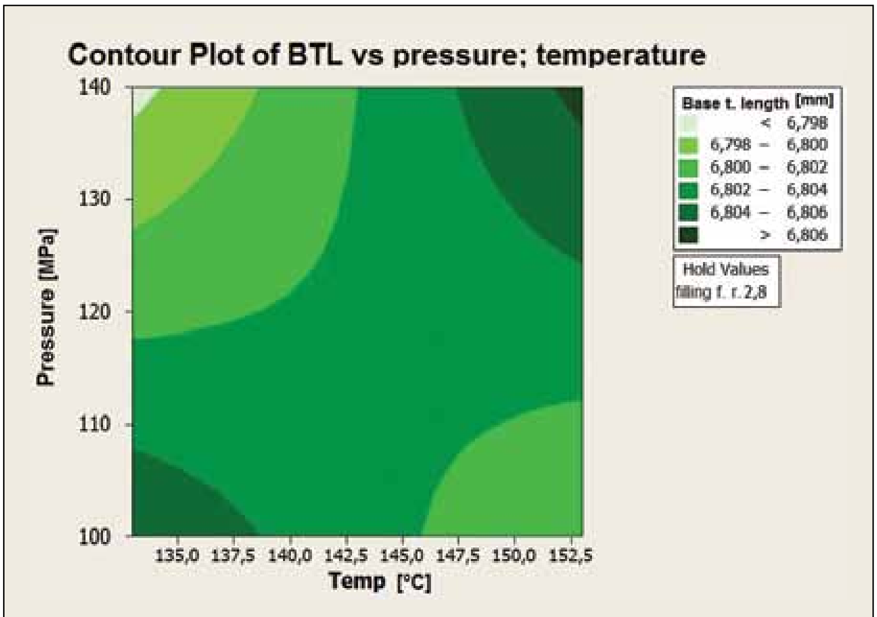

Figure 3. *Influence parameters of base tangent length in contour plot.*

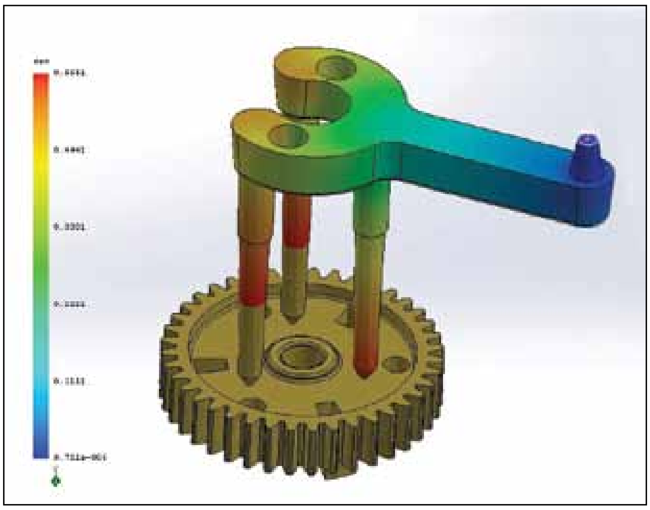

Figure 4. *Filling analysis of non-modified feed system.*

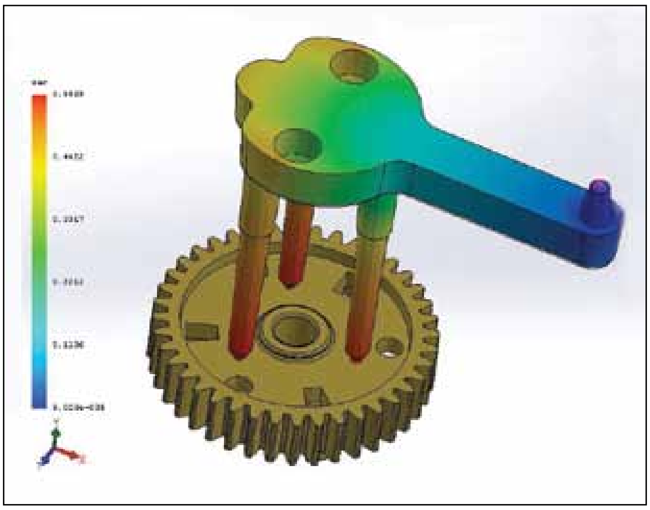

Figure 5. *Filling analysis of modified feed system.*

4.2 Eccentricity of mould inserts

Eccentricity is defined as the distance between the theoretical and actual centres of a gear. By using a double flank roller tester, the magnitude and orientation of the test gear's eccentricity can be determined [7].

Because the software of the tester can show only one measurement at a time, a specific Windows application DF Runout was developed in MATLAB graphical interface. The layout of the application is shown in *Figure 6*.

With this application, it is possible to open and view as many measurements as necessary and to find average values of the runout error and eccentricity. Based on the average eccentricity (right graph in Figure 6), the gear teeth insert was shifted relatively to the gear axle (gear body insert). By adding a welded layer of 0.01 mm to 0.02 mm thickness on one side of the insert and grinding the other side, the runout error was reduced up to 30 % with the improvements of the gear's eccentricity.

4.3 Correction of gear teeth

The runout error can be reduced with the teeth insert shifting, but the shrinkage deviations still remain on the circumference of the gear. In order to improve the whole geometry of the gear, a program was developed in MATLAB to compensate the shrinkage differences. Its

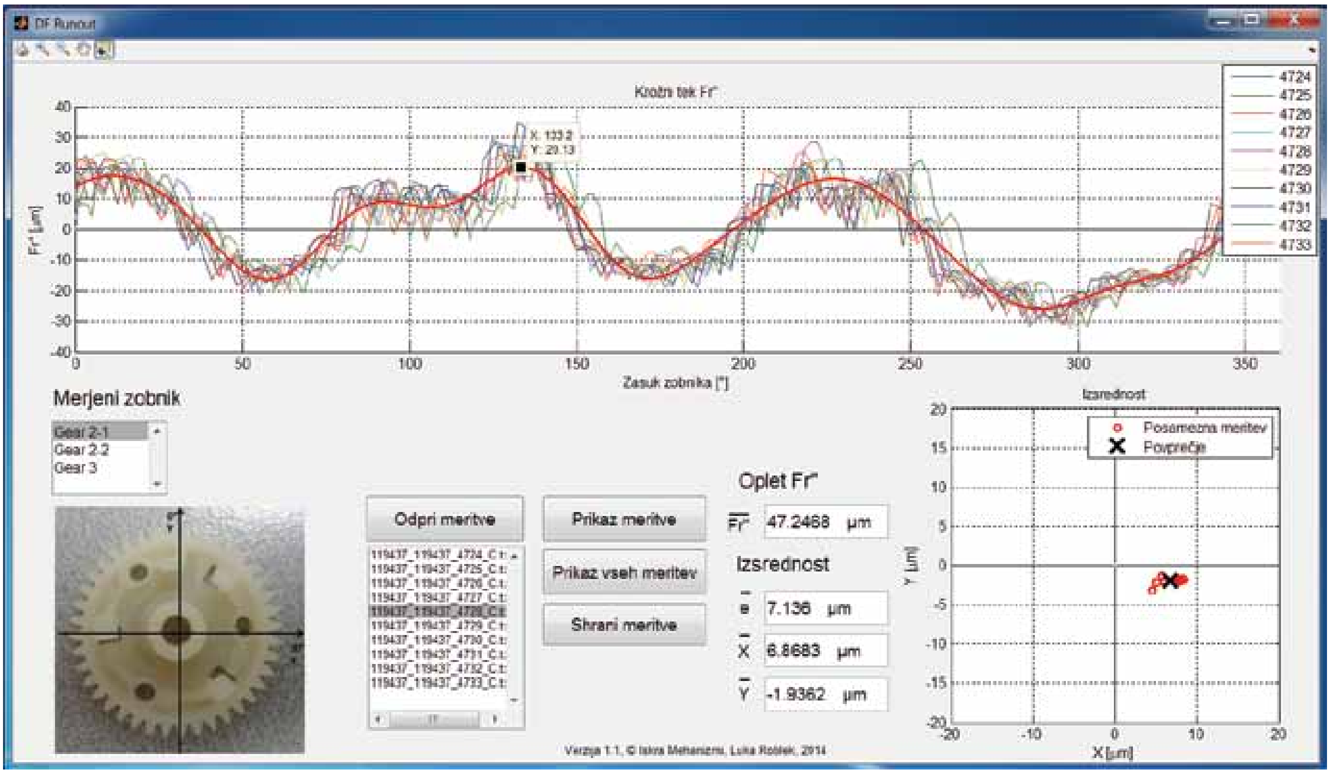

Figure 6. *Runout measurements in the application DF Runout.*

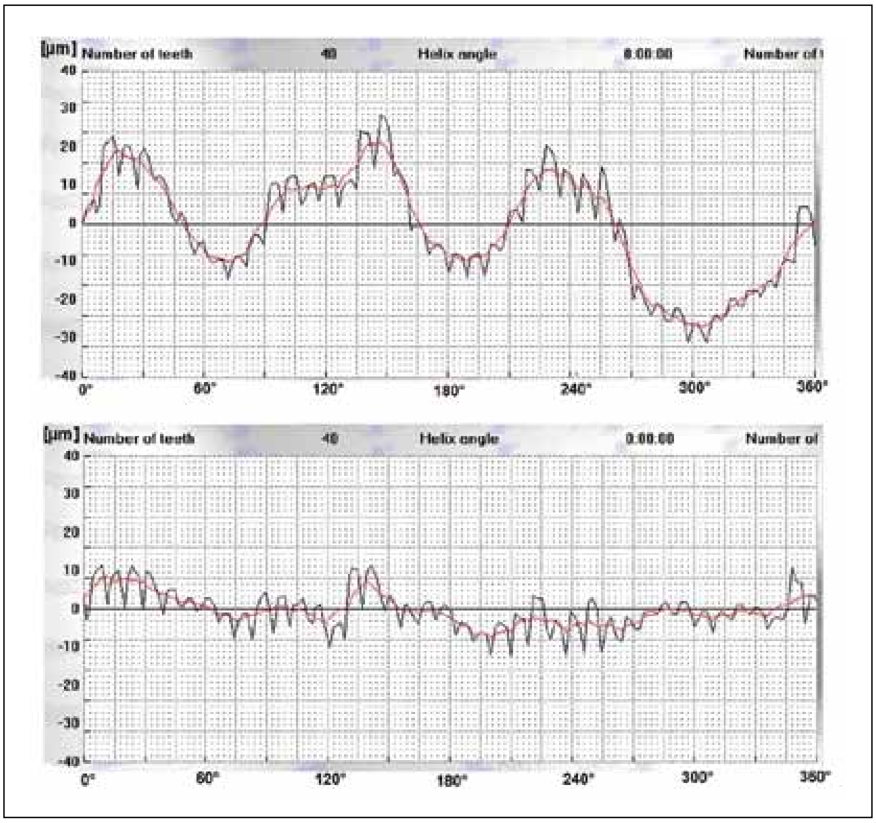

Figure 7. *Runout before (upper graph) and after the correction (lower graph).*

bases were the original gear tooth profile and the average runout error from the DF Runout application. The gear teeth were transformed to an array of points and the values of runout were subtracted from that array in order to get the deformed gear teeth. The program exports the new gear shape into DXF file, which was used to cut a new gear teeth insert with wire EDM.

The runout measurements of the gear before and after the correction are compared in *Figure 7.* Results showed up to 65 % reduction of gear runout as it is shown in *Figure 8.*

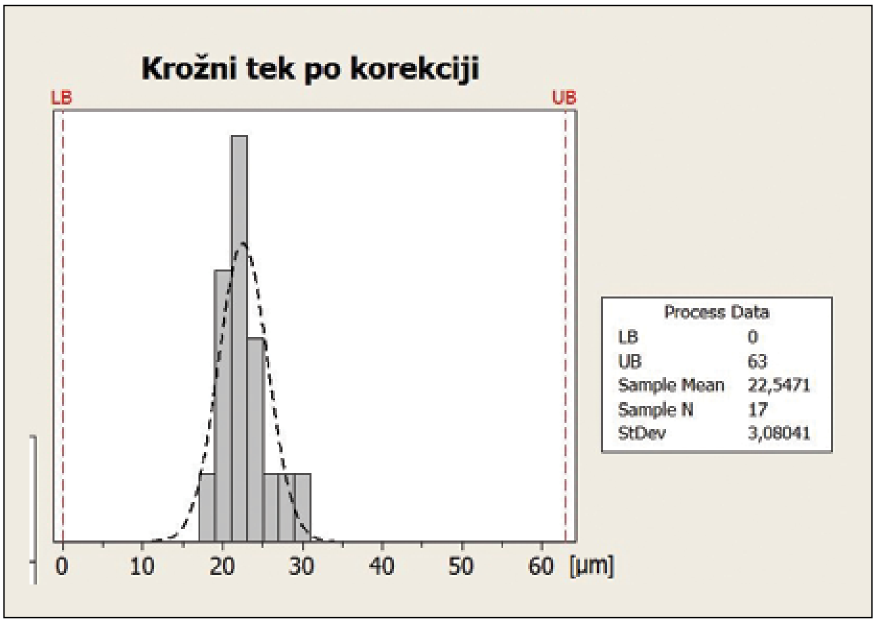

Figure 8. *Runout measurements after the correction*

5 Conclusion

With injection moulded plastic gears it is difficult to ensure precise gear tooth dimensions because of the shrinkage and complex geometry. The double flank runout error of the gears before optimisation was around 60 µm. First, the optimisation of the moulding parameters was done. By increasing the packing pressure and mould temperature, the runout error was reduced for about 10 %. The eccentricity was found to be an important contributor to the double flank runout error. By shifting the gear teeth insert relatively to the gear axle, eccentricity and runout were reduced. Additionally, the original gear tool insert geometry was modified according to the runout error measurements. In the end, the runout error was reduced to nearly 20 µm.

Precise gears are a key component of mechatronic modules. Therefore Iskra Mehanizmi will continue with systematic research and the practising of precise injection moulding.

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Natančno injekcijsko brizganje polimernih zobnikov

Razširjeni povzetek

Podjetje Iskra Mehanizmi razvija in proizvaja več vrst mehatronskih produktov in hišnih aparatov, kjer so vgrajeni polimerni zobniki. Uporaba tovrstnih zobnikov je v zadnjih petdesetih letih močno narasla, še posebno v avtomobilski industriji. Zaradi zmožnosti obratovanja brez mazanja v veliki meri nadomeščajo kovinske zobnike. V primerjavi s slednjimi so tudi veliko lažji, manj hrupni, imajo nizek koeficient trenja in so cenejši za izdelavo. Izdelujejo se z injekcijskim brizganjem, ki nam omogoča proizvajanje zahtevnih oblik v velikih količinah na ekonomičen način. Kljub naštetim prednostim ima proces brizganja tudi svoje omejitve. Neenakomerno krčenje izdelka pri ohlajanju povzroča uklanjanje in zvijanje, kar pa pri zobnikih vpliva na obliko zobnih bokov, razdelek, izsrednost, krožni tek, itn. V podjetju se za spremljanje kvalitete zobnikov v proizvodnji uporablja radialna dvobočna kontrola, ki nam med drugim prikaže tudi krožni tek pri radialni dvobočni kontroli. Članek obravnava izboljšave procesa injekcijskega brizganja in orodja za brizganje z namenom zmanjšanja omenjenega krožnega teka. Narejena je bila analiza merilne sposobnosti merilne opreme, nato pa se je po metodi načrtovanja eksperimentov določilo vplivne parametre na krožni tek in njihove optimalne vrednosti. Na osnovi meritev in simulacije brizganja je bilo orodje spremenjeno za večjo stabilnost samega procesa. Razvita sta bila Windows aplikacija za učinkovitejšo obravnavo krožnega teka ter namenski program za modifikacijo zobnih bokov. S temi izboljšavami se je doseglo stabilen proces brizganja zobnikov in zmanjšanje napake krožnega teka za skoraj 65 %.

Ključne besede: Polimerni zobniki, injekcijsko brizganje, metoda načrtovanja eksperimentov, korekcija oblike zob