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Influence of Tribological Processes of the Mechanisms of Free Motion on Operational Characteristic of the Impulsive Friction Variators

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The impulsive friction variators are very specific transmitters. They are characterised by the periodical impulse transmission of power and motion. For research purposes, the device was made to simulate wear of the tribomechanical system: external envelope (coulisse) – roller and roller-shaft in the free motion mechanism with use of the impulsive friction variators. Monitoring of the elements of tribomechanical system was conducted by recording the changes of dimensions depending on the investigation time. Roughness parameters were measured and wear traces of the tribomechanical system were recorded. It was concluded that at the shaft (star), a dominant mechanism of wear is pitting, and that destruction of the oil film precedes the damage at the coulisse (roller). By analysing the change of the gap and influence of the change of wedging angle, it is determined that the period of intensive wear at the beginning and the period of constant wear can be differentiated. It was concluded that the change of the gap clearly represents the curve of wear of tribomechanical system. The increase of the gap has a direct influence on the wedging angle and therefore also on the increase of irregularities of the output shaft.

Utjecaj triboloških procesa mehanizma slobodnog hoda na radne karakteristike impulsnih tarnih varijatora

Izvornoznanstveni članak

Impulsni tarni varijatori su vrlo specifični prijenosnici. Karakterizira ih impulsni periodični prijenos snage i gibanja. U cilju istraživanja izrađen je ispitni uređaj za simuliranje trošenja tribosustava: vanjski prsten (kulisa) - valjčić i vratilo - valjčić u mehanizmu slobodnog hoda pri radu impulsnih tarnih varijatora. Praćenje elemenata tribosustava vršeno je snimanjem promjena dimenzija u ovisnosti o trajanju ispitivanja. Mjereni su parametri hrapavosti i snimani tragovi trošenja elemenata tribosustava. Zaključeno je da je kod vratila (zvijezde) dominantni mehanizam trošenja pitting, a da oštećenju vanjskog prstena (valjčića) prethodi razaranje uljnog filma. Analizom promjene zazora i utjecaja promjene kuta zaklinjavanja utvrđeno je da se mogu razlučiti period početnog intenzivnog trošenja i period ustaljenog trošenja. Zaključeno je da promjena zazora jasno prikazuje krivulje trošenja triboelemenata. Povećanje zazora direktno utječe na promjenu kuta zaklinjavanja, a samim time i na povećanje neravnomjernosti rotacije izlaznog vratila.

1. Introduction

Speed variators are transmitters of power and motion where the number of rotations of the output shaft is changing in a certain range, with constant rotation of the input shaft. Unlike other ways of transmission, energy does not transmit continuously, but in the form of periodic impulses. This transmitter makes two types of movements.

First, rotating motion with constant angular velocity of the input shaft transforms into oscillatory motion of elements on the output shaft. Then the oscillatory movement by the mechanisms of free motion (FMM) transforms into rotation movement of the output shaft. To reduce the problems caused by delays in transmission or an uneven speed during the construction, several fits of transformational mechanisms and FMM are connected together. These mechanisms have been rotated in relation to one another for the $\Delta\varphi$ angle.

As a result of tribological processes on the contact surfaces of the observed triboelements of FMM, different kinds of wear arise. They differ from each other by the manner and intensity, and also by the final consequences they have. Reliability and durability of FMM depends on the development of wear processes in the basic tribomechanical systems.

2. Tribomechanical Systems in FMM

FMM with impulsive variators converts oscillating motion of the coulisse into rotating movement of the output shaft. It consists of three main parts:

- exterior ring (the coulisse)
- input shaft (star), and
- rollers.

The mechanism of free motion (Figure 1) is turned on during the wedged state that is caused during rotation of the star (2) compared to the outer ring (1) in the clockwise direction, or rotation of the outer ring (1) around the star (2) in the counterclockwise direction [1-4].

During this process, the rollers are wedged between the star and the outer ring integrating the basic elements of FMM. During relative motion of the outer ring in the opposite direction, the rollers are unwedged and the mechanism is turned off [5- 8].

Free motion lasts from the end of unwedging to the beginning of wedging in the new cycle. If we mark rotation speed of the outer ring with ω_1 and rotation speed of the star with ω_2, then for the whole period of free motion $\omega_1 > \omega_2$. The direction of ω_1 is taken as positive.

The effect of dynamic load on the elements of FMM causes oscillatory processes in the period of free motion and it can lead to disruption of contact between the roller and working surfaces of the inner and outer elements. Oscillations of the roller increase losses in the period of free motion and therefore jeopardize proper development of the wedging process. The absence of contact at the moment when the wedging process should start is unacceptable because the wedging process can start late or even be completely missed. Inappropriate time of the wedging process can cause great dynamic load and increased wear of the mechanism elements.

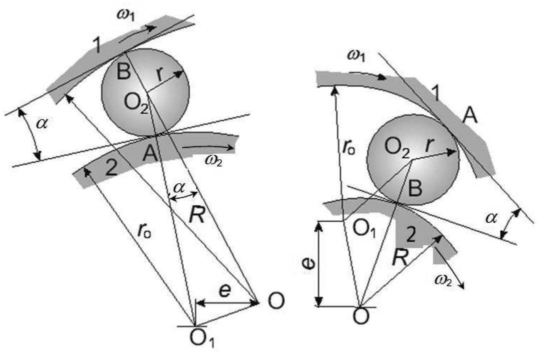


Figure 1. Wedging angle

Slika 1. Kut zaklinjavanja

According to its structure, FMM belongs to a higher hierarchical class of the tribomechanical systems, because they can be subdivided in several basic tribomechanical systems.

In FMM with impulsive variators (Figure 3), we distinguish the following tribomechanical systems:

- coulisse - roller,
- coulisse - cylinder carrier,
- coulisse - cylinder carrier (side contact),
- coulisse - capsule (side contact),
- roller - shaft,
- roller - compression spring,
- roller - capsule (side contact),
- roller - cylinder carrier (side contact).

Figure 2. Elements of impulsive friction variators

Slika 2. Elementi impulsnih trenih varijatora

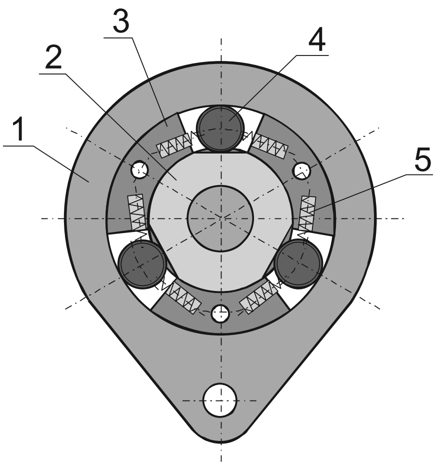


Figure 3. Free motion mechanism (FMM): 1 - coulisse, 2- shaft, 3 - cylinder carrier, 4 - cylinder, 5 - spring

Slika 3. Mehanizam slobodnog hoda (MSH): 1 - vanjski prsten, 2 - vratilo, 3 - nosač valjčića, 4 - valjčić, 5 - pruga

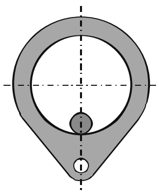
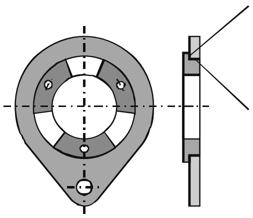
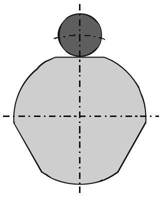
Table 1 shows an appearance of tribomechanical systems and their basic types of movement that appear. The mechanism of transmission of power and motion by friction in principle is contained in the molecular - mechanical nature of friction. The process that resists to relative motion of the object is used for the primary function and purpose of the transmitters. Friction in FMM consists of: rolling friction with sliding, sliding friction, friction in the lubricant. The mutual complex connection makes it difficult to analyze any kind of friction. Rolling friction with sliding occurs in the process of wedging the cylinder with external and internal envelope. It is partly caused by sliding in the triboelement contact zone and also with appearance of flexible hysteresis. Flexible hysteresis is caused by the deformation of loaded triboelements (rollers, external and internal envelope), whereby the resulting work of unload is only partially used for the motion and the rest of it goes into heat. Sliding friction occurs in the external envelope (coulisse) contact with the cylinder carrier. Under normal conditions of exploitation, sliding friction in the tribomechanical systems FMM is negligible compared to other types of friction. Friction in the lubricant consists of the internal friction, a result of relative motion between lubricant molecules during mixing, and the outer friction that occurs when moving and squeezing the excess funds of lubricant with elements in contact. Friction and friction losses increase with increase of rotation number in FMM, viscosity and excess of the oil in contact [9- 11].

The following items affect the development of the tribological processes in the contact zones of FMM:

- elements material quality,
- production technology of the contact surfaces,
- thermochemical kind of processing,
- load of elements in contact,
- quality of lubricants and cooling liquids, etc.

Different kinds of wear and damages can occur on the elements of tribomehanical systems of FMM. On particular FMM, several types of wear may occur but there is always one which is dominant and it determines the future direction of development of the tribological processes and final service life of FMM or pulse variator as its part. Which forms of wear occur and which will be dominant depends on many factors: exploitation, construction, etc. Determining the participation of certain types of wear in total wear of the whole gear is very difficult. Visual quantification is performed on the basis of appearance of the worn surfaces. The main criteria of working ability of cylindrical FMM impulse gear mechanisms are the ability to wedge without traction and maintain the contact strength of most loading elements. FMM with cylindrical rollers gets out of order due to fatigue breakage and wear of the working surfaces star. FMM with an eccentric roller lost working ability due to destruction of the cylinder surface.

Table 1. Tribomechanical systems in FMM
Tablica 1. Tribomehanički sustavi u MSH

Tribomechanical system and type of movement		
1		coulisse - roller (vanjski prsten – valjčić) rolling with sliding (kotrljanje s klizanjem)
2		Coulisse - cylinder carrier -side- (vanjski prsten – nosač valjčića -bočno-) sliding (klizanje)
3		coulisse - cylinder carrier (vanjski prsten – nosač valjčića) sliding (klizanje)
4		roller – shaft (valjčić-osovina) rolling with sliding (kotrljanje s klizanjem)

Breakage and wear may be limited by increasing the hardness of the material cylinder, stars and envelopes through thermal treatment, using insertion of hard alloys, reducing the roughness of contact surfaces, increasing the accuracy during production of the cylinders, entire mechanism, as well as its assembly.

3. Description of experiments

Experimental testing of the power carrier impulsive lever variator, with four types of transformation mechanisms and FMM, is conducted on a specially made test table (Figure 4) [12].

The tested gear (2) was connected with the driving aggregate (1) over belted gear (4), (electric motor P = 0,55 kN, n = 2880 rpm). The brake disc was set on the output shaft of variator (6) that rotates in a magnetic field of the electrical brakes (7), and thus made permanent load of the gear.

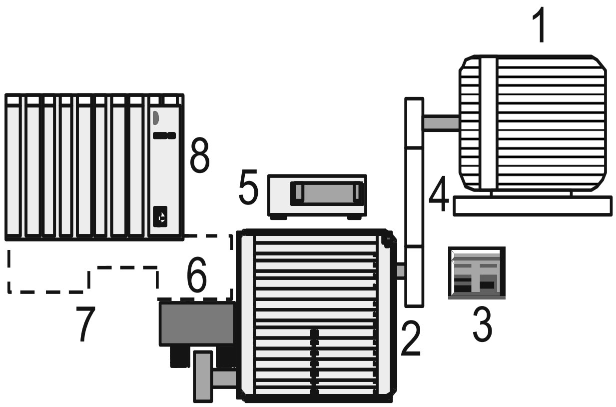


Figure 4. Schematic diagram of the test table
Slika 4. Shematski prikaz ispitnog stola

A special measurement system (Figure 5) was designed for tribometrical testing of the tribomechanical system FMM impulsive lever, friction variator. The main components of that system are mentioned below:

- test table,
- device for analysis and measurement of surface roughness, TALYSURF 6,
- device for wear measuring OPTON (ZEISS),
- computer, printer.

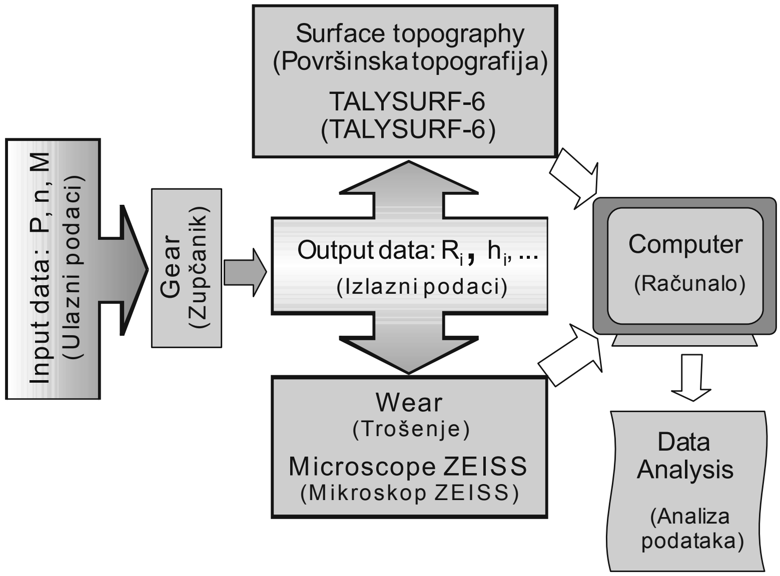


Figure 5. Schematic review of the measuring system
Slika 5. Shematski prikaz mjernog sustava

Operational regime of the tested gear was selected. The loading of the variator output shaft was achieved with brakes. This defined the working conditions with a known geometry of the contact. After establishing the selected operational regime, the carrier is put into operation for a certain number of hours, then disassembly and measurement of the parameters of roughness and wear were performed [13].

Tribomechanical systems of tested FMM (Table 1), where tribological processes are most affecting the functioning of the mechanism and whose changes were followed in the process of wear, are:

- coulisse - roller,
- shaft - roller.

Changing of the diameter of the hole on the coulisse Δd_{cou} (Figure 6) was measured on the computerized measurement device Opton (ZEISS) with scanning in 500 points. In Figure 7, there is the record of the measurements. Measurement results are shown in Table 2 and Figure 9.

$$\Delta d_{cou} = D_{cou\ i} - D_{cou\ 0}, \quad (1)$$

$D_{cou\ i}$ - measurements during the testing
$D_{cou\ 0}$ - initial value of the coulisse hole.

Measuring of shaft (stars) wear was performed by the measuring device OPTON, Figure 8.

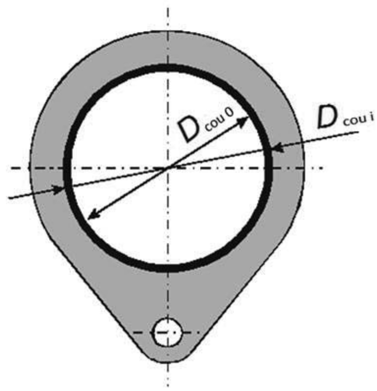


Figure 6. Coulisse
Slika 6. Vanjski prsten

Measuring of cylinder wear (a measure ϕ6) was performed by a micrometer with prism TESAMASTER, measuring range from 0 to 25 mm of measurement accuracy ± 0,001 mm. A change of the cylinder diameter

$$\Delta d_{cyl} = D_{cyl\ 0} - D_{cyl\ i}, \quad (2)$$

is given in Table 2, with:

$D_{cyl\ 0}$ - cylinder diameter measurements before the start of operation,

$D_{cyl\ i}$ - cylinder diameter value measured after a certain number of working hours of FMM or variator.

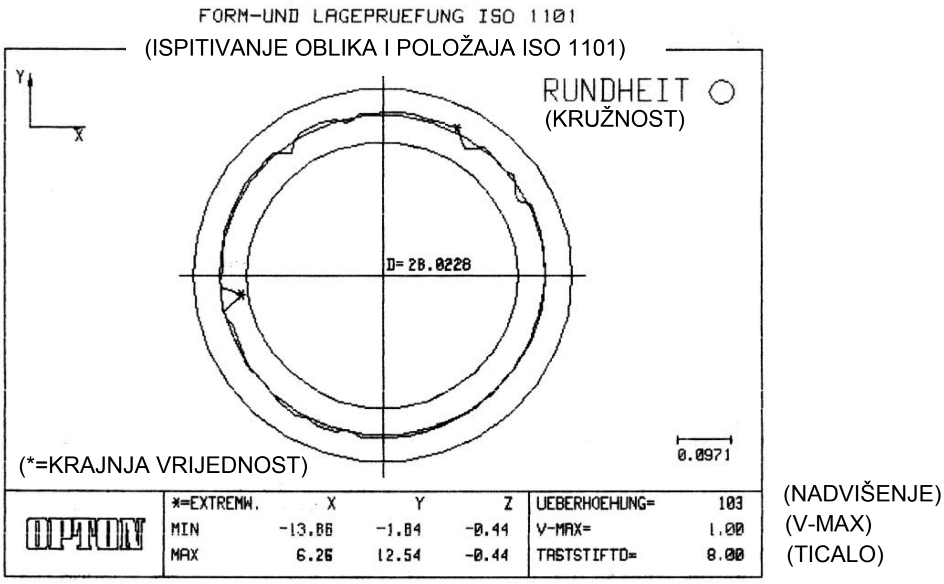


Figure 7. Recorded measurements of coulisse hole wear
Slika 7. Zapis mjerenja trošenja otvora vanjskog prstena

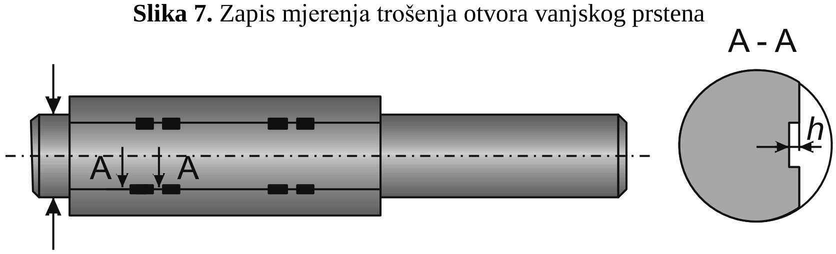


Figure 8. Places of measuring shaft wear
Slika 8. Mjesta mjerenja trošenja vratila

Table 2. Changing of the cylinder diameter Δd_{cyl}, mm
Tablica 2. Promjena promjera valjčića Δd_{cyl}, mm

Element name/Ime elementa		Operational time, h/Vrijeme rada, h				
		7	35	80	170	300
Coulisse/ vanjski prsten	coulisse 1/ vanjski prsten 1	0,0058	0,0130	0,0168	0,0243	0,0397
	coulisse 2/ vanjski prsten 2	0,0089	0,0160	0,0190	0,0261	0,0381
	coulisse 3/ vanjski prsten 3	0,0070	0,0163	0,0230	0,0265	0,0327
	coulisse 4/ vanjski prsten 4	0,0083	0,0150	0,0182	0,0257	0,0375
Shaft/ Osovina	measuring point 1/ mjerna točka 1	0,0032	0,0040	0,0063	0,0162	0,0439
	measuring point 2/ mjerna točka 2	0,0026	0,0037	0,0067	0,0164	0,0420
	measuring point 3/ mjerna točka 3	0,0028	0,0042	0,0068	0,0178	0,0455
Cylinder/ Valjčić	$\Delta d_{cyl} = D_{cyl\,0} - D_{cyl\,i}$	0,0028	0,0086	0,0110	0,0187	0,0410

The Figures from 9 to 11 show curves of the wear of elements in the contact mechanism of the observed tribomechanical systems of FMM impulsive lever friction variators and the Figures 12 to 14 show wear of elements after 300 hours of work.

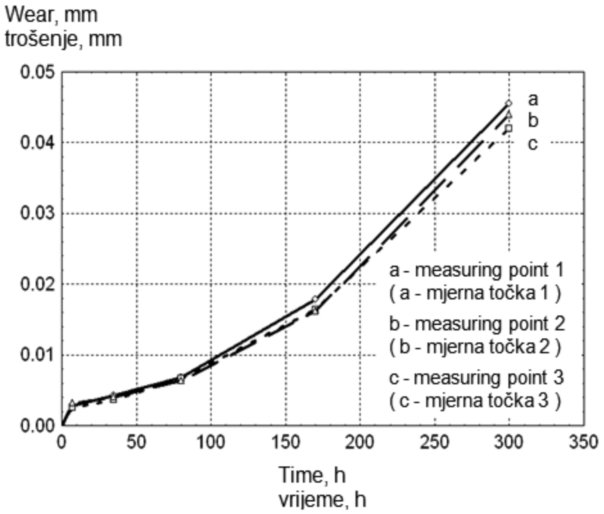


Figure 9. Curves of shaft wear (star)
Slika 9. Krivulje trošenja vratila (zvijezde)

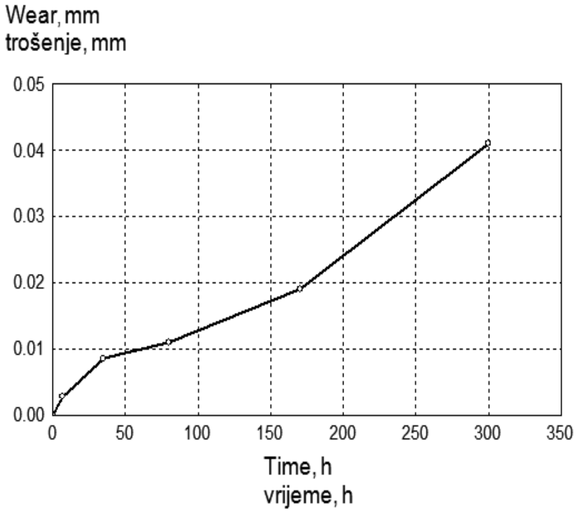


Figure 10. Curve of cylinder wear
Slika 10. Krivulja trošenja valjčića

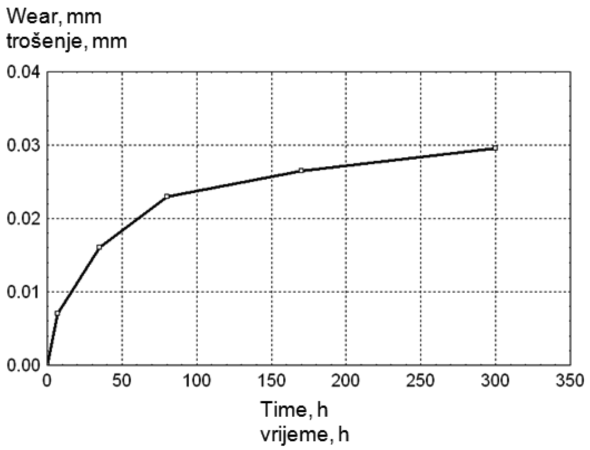


Figure 11. Curve of coulisse wear
Slika 11. Krivulja trošenja vanjskog prstena

Figure 12. Appearance of worn coulisse
Slika 12. Izgled istrošenog vanjskog prstena

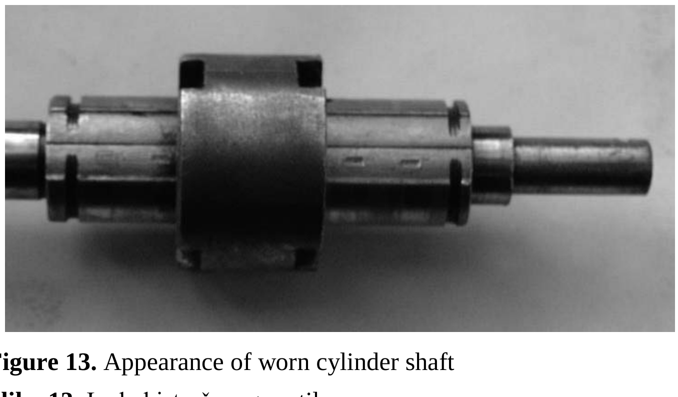


Figure 13. Appearance of worn cylinder shaft
Slika 13. Izgled istrošenog vratila

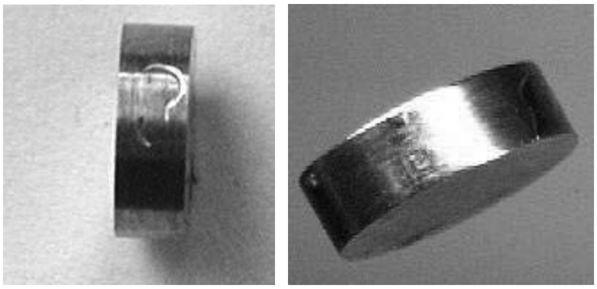


Figure 14. Appearance of worn cylinder
Slika 14. Izgled istrošenog valjčića

Figure 15 shows the coulisse (from the exploitation) on which the adequate thermochemical processing is not implemented. The coulisse was withdrawn from the operation after approximately 10 hours.

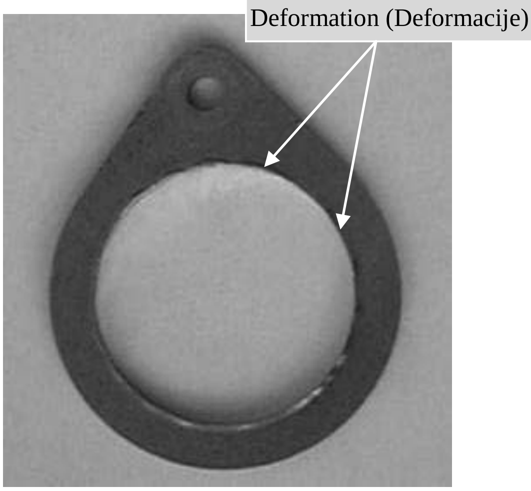


Figure 15. Deformation of coulisse caused by poor thermochemical processing
Slika 15. Deformacija na vanjskom prstenu izazvana lošom termokemijskom obradom

4. The analysis of the results

The elements of FMM during the operation are exposed to frequent changes of load and strong fatigue within materials of the entire system. The presence of cyclic strain fields causes appearance of fatigue in FMM, appearance of micro cracks, craters, as well as large plastic deformation, which can cause permanent damage and mechanism failure. Wear types of the observed tribomechanical system elements (cylinder, coulisse, and shaft) are: adhesive, fatigue and abrasive wear.

In the shaft (star), the prevailing form of wear is fatigue wear (pitting) with a pronounced process of plastic deformation of the contact surface, which is a direct consequence of contact of the elements with different hardness (shaft 48 HRC, roller 62 HRC), in conditions of high normal pressures, strains. Due to the relative movement of the cylinder over the shaft and large specific pressures that follow the process of wedging, it comes to increasing plastic deformation of the surface layers and to the appearance and increase of microdefects in it. After a certain number of operational cycles or load cycles, separation of small pieces of material from the surface may appear, which can cause increased abrasive wear on these elements. In order to reduce the intensity of fatigue wear, it is desirable that the contact surface of the elements has the finest quality of surface.

The adhesive wear that appears in the zone of contact roller - shaft and roller - coulisse preceded the destruction of lubricant layer, because of too high load during the wedging. That situation leads to increased contact pressure and temperature which caused plastic deformation and appearance of scoring at the contact surfaces. The coulisse appears as a critical part in the motion and power transfer. During the operation, it is exposed to cyclic loadings followed by frequent strikes due to unbalanced rotations of the external shaft. The oil film at the point of contact of the coulisse with the roller and the roller carrier is destroyed during the wedging process. As a result of that, increased wear in combination with material fatigue and very frequent gear overload leads to coulisse failure.

If the curves of wear and roughness parameters are observed, it can be noticed that smooth work period of the surface (for most elements) starts after about 50 operational hours. After that normal wear process begins. The start of smooth work period is characterized by the change of the surface topography, because of transitional technological topography in the experimental part. This process is followed by a sudden change in the roughness parameters, roughness peaks were taken and the profile becomes more unified. Due to high local loads, which are necessary for power transmission and friction motion, changing of roughness is obtained after finishing of contact surfaces.

At the beginning of the examination, an intensive removal of material from the surface occurs, which can be seen from the curves of wear. The most expressed peaks of roughness were taken away, so the profile becomes more equal and less rough. Roughness parameters reduced by the end of this period. This proves that the surface tends to become balanced in terms of topography. A period of normal wear begins after a start of smooth work period. Roughness parameters increase slightly, the surface has changed in exploitation, and wear is settled. The shaft is an exception, because the roughness parameters increase sharply to about 200 operational hours. The curves of wear show increased wear, which is consistent with the previous, and if this trend of increase of wear continues, it may be normal to expect a quick switch from normal to destructive wear.

Wear intensity of elements of the tribomechanical systems in FMM, on tested impulse variator is function of a large number of influential factors. The most influential factors are: type and quality of surface and thermo-chemical processing, size of the normal loads and speed of relative movements between the elements of the basic tribomechanical systems. The changing of the gap occurs as a result of wear of FMM elements. It directly affects the change of wedging angle and also the increasing of rotation unevenness of the output shaft of the carrier (FMM star). In Figure 16, the gap changes are calculated on the basis of geometrical dimensions for different values of worn elements of the mechanicms in the place of the 4th coulisse.

A trend of gap growth is done by the basic laws of tribological processes of wear. On the curve of axial gap dependence from operational time of transmitter, a period of initial and also a period of constant wear can be noticed. In reference to gap changes, a diagram demonstrated the wear curves on the observed triboelements. A change of the gap between the elements in contact, cylinders and envelopes, as a direct result of elements wear of FMM, affects the change of wedging angle, and thus the increasing unevenness of rotations on the output shaft of the carrier.

The observed variators have the four phase shifted coulisse for $\pi/2$ angle which alternately switches on and off. Appearance of tribological processes on the elements in contact, angles changing also prolongs the time of wedging. As on the polished FMM, time of wedging is different for each of the coulisse (depending on the geometry of coupling) appearance of wear; it is extended for a definite time interval Δt on each coulisse that causes new disturbance evenness of rotation of the output shaft. Wedging angle change is given in Figure 17, calculated for the three measuring sites in the place of the 4th coulisse.

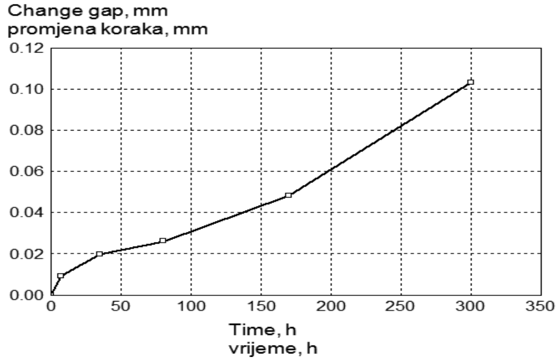


Figure 16. Gap changes curve
Slika 16. Krivulja promjene zazora

In FMM with more cylinders, each cylinder appropriates a different wedging angle. The errors in production of the main elements of FMM and especially assembly errors (unidentical axes of the envelope) cause different values in different wedging angles, on different contact surfaces. In the first part that value is lower, but in the second it is higher than nominal. This phenomenon is especially pronounced in the mechanisms with linear profile, which is also the main reason for the selection of curving profile.

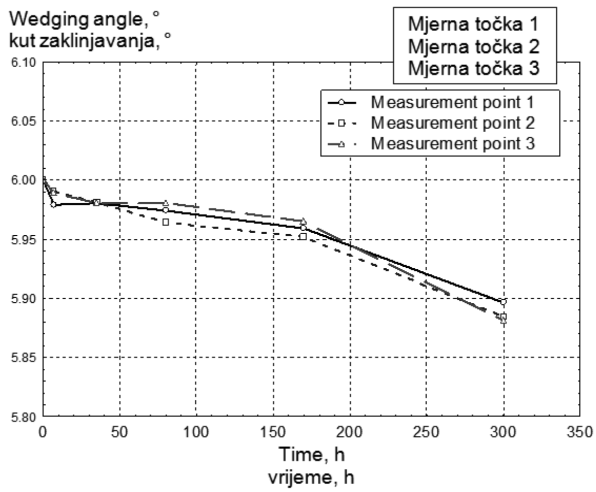


Figure 17. Change of wedging angle
Slika 17. Promjena kuta zaklinjavanja

5. Conclusions

The appearance of tribological processes on the contact surfaces of the tribomechanical elements of FMM impulsive friction variators is one of the main causes of loss of accuracy and work reliability. Rolling resistance appears during the operation of these tribomechanical systems as the inevitable occurrence of the process of rolling cylinder between envelopes. It has a very complex nature and must be observed in the context of all causes and factors that affect it. The dominant mechanism of wear on elements of the observed tribomechanical system is fatigue, and also adhesive and abrasive wear.

Wear intensity on elements of the observed tribomechanical systems is a function of the large number of influential factors such as types and quality of surface and thermochemical processing, the size of the normal load and speed of relative movement between the basic, critical tribomechanical carrier systems.

As a result of wear of FMM elements gap, changes appear in it, which directly affects the change of wedging angle and consequently the increase of uneven rotation of the output shaft carrier (FMM stars). To reduce the wear on contact surfaces of the tribomechanical basic elements of FMM impulsive friction variators and extended operational life of the gear, it is necessary to consider: the selection of material for triboelements, to improve the contact surface topography, consider the economic confirmation for production of the FMM elements with hard plate on contact surfaces. A classical cylindrical roller is replaced with a convex cylinder. Under the load, convex cylinders are compressed and they have the same shape of contact surface as the cylinder. Also, their disposal of load is very good, even at very high loads. Cylindrical rollers are exposed to high tension concentration on the edge, which makes them very exposed to margin pitting and short service life. The convex cylinders are less exposed to wear, and also compensate possible deviations in the phase of construction and production, even in conditions of high tensions as in FMM.

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