Polymer as Metal Replacement for Pneumatic Drives Rods Working in Dry Friction Condition

GEANINA MARCELA PODARU*, SORIN CIORTAN, IULIAN GABRIEL BIRSAN
Universitatea “Dunărea de Jos” din Galaţi, 47 Domnească Str., 800008, Galati, Romania

The work presents a study on a possible solution of metal replacement for pneumatic drives rods working in dry friction condition. If the total absence of lubricant and others contaminating agents is required, due to specific working environment, the pneumatic drives use is recommended. The rod sealing system is elastomeric lip seal based and works, in this case, in linear sliding dry condition. The authors tried to establish the way that polymeric material replacing the metallic rod behaves, taking into account the working conditions. Considering that the sealing system failure is due to wear, a closer investigation is performed at surfaces level by optical and 3D reconstruction methods. The observations allowed an optimization of polymeric rod rubber lip seal system in dry sliding conditions from the materials choosing point of view.

Keywords: dry friction, elastomer-plastomer couple, linear sliding motion

Due to the linear reciprocating motion of the rod pneumatic drives shows some particularities of velocities distribution along the rod stroke, (fig.1). If the rod mass is high enough, as in metallic rod case the inertia forces can lead to unwanted effects on the motion precision. These aspects must be taken into account in the design stage especially for pneumatic actuators [1]. According to them, a lower rod mass, with the same mechanical performances, is highly desirable. From this point of view the polymeric materials are the best choice. They offer low inertia forces and compatibility with high aggressive environments, especially where metals cannot be used. From the mechanical strength point of view, the metals performances can be easily equalized [2].

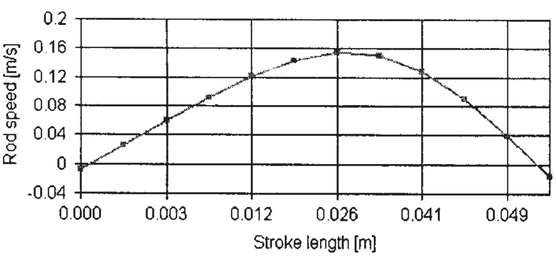


Fig. 1 . Rod speed versus stroke length

If the sealing system of pneumatic drive rod works in dry friction without lubricant, the polymeric materials used must comply with specific requirements. In these cases specific phenomena, as stick-slip - at the strokes’ ends where the static friction get into dynamic friction or in very low working frequency can be observed. The characteristic property of polymers to develop in dry friction a transferred material film, provide a “third body” [3] in the system leading to a complex evolution of the wear processes, from adhesion to abrasive, with a non-uniform distribution along the rod. The presence of this “third body” has a positive influence on system tribology but, eventually, the wear leads to seal failure. In the paper is analysed the way the transferred material film act on seal-rod system behaviour, investigating the possibility of optimization and extension of seal working life.

Experimental part

Methods and materials

In order to investigate the polymeric rods behaviour, an especially designed test rig was used (fig.2). The frequency controlled electric drive allows performing tests at both very low and to high sliding speeds. The air pressure and friction force are recorded by appropriate sensors and gauges. A special parameter was defined for seal efficiency evaluation – pressure drop rate [4], as ratio between pressures losses and corresponding time interval.

Taking into account that the temperature has a major influence on the polymeric materials behaviour and transferred film formation [5], a thermo-graphic camera was used for this parameter monitoring and recording [6].

Two polymeric materials (polyoxymethylene - POM and polyetheretherketone - PEEK) were chosen for tests.

POM is a semi-crystalline thermoplastic material that provides high strength and stiffness, enhanced dimensional stability, very low moisture absorption and is easy to machine. From tribological point of view, POM is characterized by a low coefficient of friction, good wear and abrasion resistance. Also, POM shows a wide range

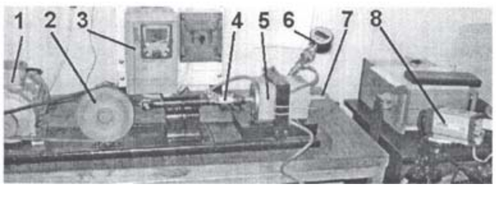


Fig. 2. Rods’ testing rig 1-electric drive; 2-eccentric; 3-frequency converter; 4-friction force gauge; 5-pneumatic enclosure; 6-digital manometer; 7-polymeric rod; 8-thermographic camera

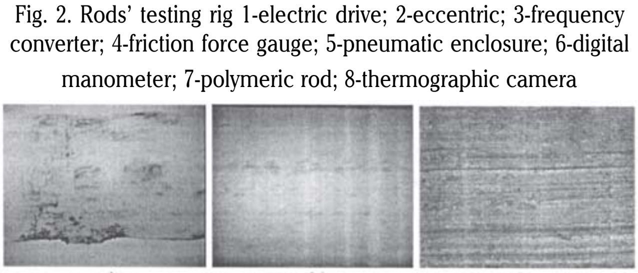


Fig. 3. POM rod wear
a) melted by overheating rod; b) stick-slip scars; c) lip-to-rod material transferred film

* email: geanina.podaru@ugal.ro

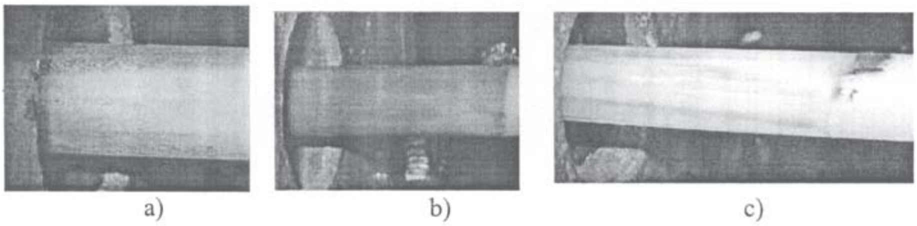


Fig. 4. Transferred material film evolution during sealing system working life
a) - initial stage, transferred film formation; b) - stabilized stage, continuous transferred layer; c) - final stage, transferred layer discontinuity and sealing system failure

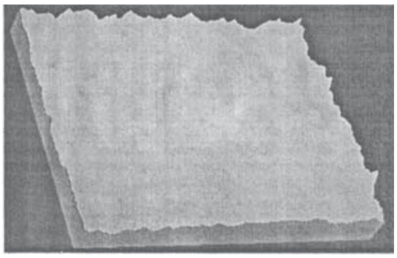


Fig. 5 . 3D reconstruction of stick-slip scars on rod surface

chemical resistance including many solvents. As a drawn back, a relative low long time working temperature can be mentioned (~ 115°C).

PEEK is a high performance engineering thermoplastic polymer. It shows an excellent chemical resistance, it is unaffected by long time exposure to hot water or steam. Also, the high mechanical strength can be mentioned. As tribological properties, high wear and abrasion resistance characterize the PEEK material. Comparing to POM, the long time working temperature limit is much higher (~ 250°C).

As lip-seal material, silicone rubber was chosen, this material being able to operate normally up to ~ 300°C. At the extreme temperatures, the tensile strength, elongation is far more superior to conventional rubbers. Also, the silicone rubber is an inert material and does not react with most chemicals.

Due to friction generated heat, the rod temperature can exceed the material prescribed working values, leading to catastrophic wear of the rod (fig.3a). As consequence, preliminary tests were performed in order to establish the working temperatures for each material, lower than recommended limits. The final testing parameters are presented in table 1.

Results and discussions

During the tests the presence of transferred material film from lip to rod was observed in both POM and PEEK case, allowing the division of system working life in three stages: before film formation, in presence of film material and, the final stage, when the film is disrupted and the seals is failing (fig.) 4.

The appearance and development of the transferred material film is highly conditioned by the thermal regime into the sealing system and is also influenced by the resulting surface quality of the rod after the machining process [6]. The results shown that for each tested material (POM and PEEK) there is relative tight temperature interval optimal for material transfer occurring, (table 2).

In the first stage, before film formation, the adhesion and stick-slip phenomenon are preponderant. The dry friction leads to high flashing temperatures and there is the possibility that these ones overcame the melting limit for rod material, especially in the surface layer of the rod, in contact points with the lip and as consequence in case of the materials with lower melting point (POM) specific scars occurs (fig.3b). The scars are more obvious at the strokes ends, where the dynamic friction goes to static friction and vice-versa. Due to the rubber lip-seal elasticity, the sealing system is an oscillating one [7]. When the stick-slip occurs, the system is excited and the scar pitch can provide information about the modal frequency of the system. Using the 3D reconstruction as investigation method [8], the scars generated by stick-slip and adhesion on POM rod surface can be visualised (fig.5).

During the first stage, due to friction generated heat and adhesion, the transferred film formation occurs [9], as continuous layer of lip material on the rod (fig3c). The sealing system passes to the second stage of working life, the stage when the transferred material film has a positive influence on sealing tribology and efficiency, acting as a lubricant [10] and as a semi-liquid sealant, covering the scars occurred in the previous stage.

In figures 6 and 7 are presented the evolution of air pressure losses and friction force during the sealing system working life for POM and PEEK rods, respectively. It can be observed the influence of transferred material layer, as an improving factor, leading to air losses stabilization and to friction force decrease (A areas). Some variations of friction

Parameter	Value		Material	
Short time working temperature limit (<10 hours) [°C]	POM	PEEK	POM	PEEK
	140	310		
Long time working temperature limit (>10,000 hours) [°C]	POM	PEEK		
	~ 115	~ 250		
Stroke length [mm]	50			
Air pressure [bar]	8; 4			
Rod diameter [mm]	8			
Rod-Lip tightening difference [mm]	0.15			
Motion speed [stroke/min]	157; 210; 264			
	418			

Table 1
TESTING PARAMETERS AND MATERIALS

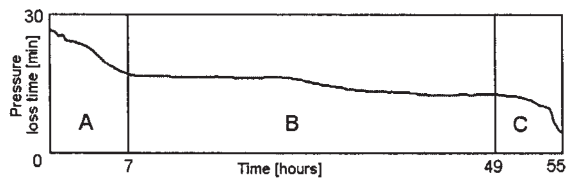
Rod material	Optimal temperature interval [°C]	
	Minimum	Maximum
POM	89.4	117.8
PEEK	96.8	190.5

Table 2
OPTIMAL MATERIAL TRANSFER TEMPERATURES

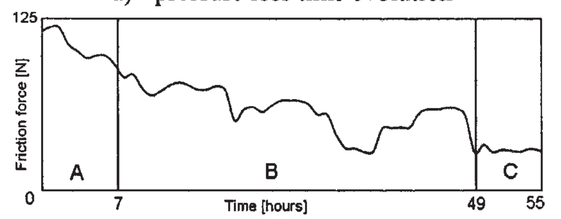
force value can be observed, caused by occasionally appearance of abrasive wear (due to hard debris detached – high values), but compensated by the transferred layer – low values (B areas). This film leads to a lower friction force and to an increased sealing efficiency; the lip wear is compensated by this film until the thickness of the lip in the contact area is almost zero (fig.8a). Eventually, the transferred material layer cannot anymore compensate the wear of the lip and the pressure losses become catastrophic (C areas). Other cause for layer disruption is the extrusion, due to high thickness, under service pressure effect.

Comparing figures 6 with 7 can be observed the influence of the rod's material on sealing system behaviour. In the same service conditions, PEEK offers a working life two times bigger than POM. If the pressure loss time evolution (fig.6b and fig.7b, respectively) is almost the same, the friction force has a dramatic increase into the latest working stage for POM rod, leading to quickly shorting the working life. This behaviour is cause by the mechanical properties differences between PEEK and POM, in presented testing conditions POM being more sensitive to abrasive wear.

The transferred material film effect on seal's tribology is not just a lubricant one but also a protective one against rod's surface damaging by abrasion with hard debris. One source of hard particles is the filler used for rubber lip, in

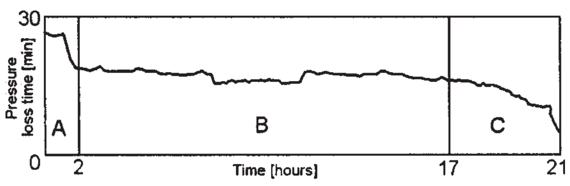


a) - pressure loss time evolution

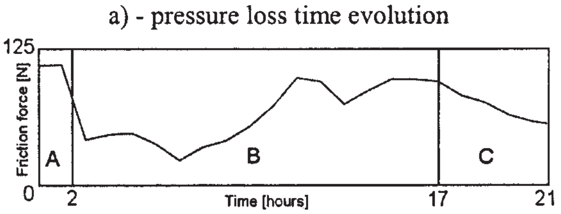


b) – friction force evolution

Fig. 6. PEEK rod, 8 bar air pressure, 210 stokes/min sliding A-initial stage, transferred film formation; B-stabilized stage, continuous transferred layer; C-final stage, transferred layer discontinuity and sealing system failure

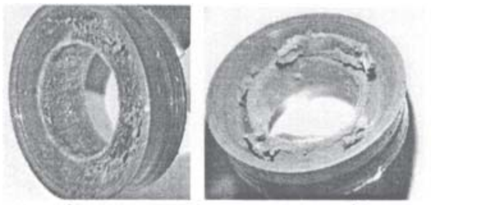


a) - pressure loss time evolution



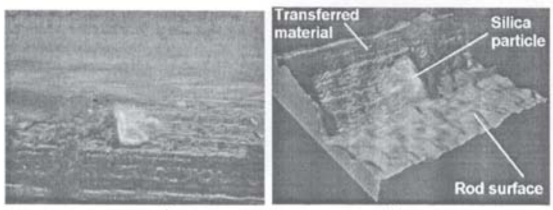
b) – friction force evolution

Fig. 7. POM rod, 8 bar air pressure, 210 stokes/min sliding A-initial stage, transferred film formation; B-stabilized stage, continuous transferred layer; C-final stage, transferred layer discontinuity and sealing system failure



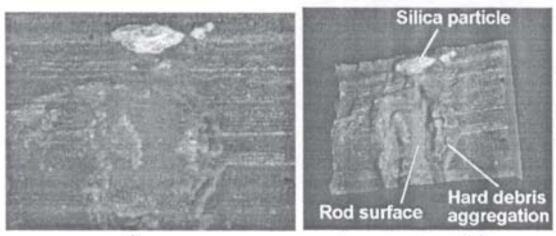
a) b)

Fig. 8 a) lip wear limit compensated by the transfer film ; b) catastrophic lip wear due to over-vulcanization



a) b)

Fig. 9. Silica particle embedded into transferred material a) on-top image; b) 3D reconstruction



a) b)

Fig. 10. Ruptures generated into transferred layer by hard debris a) on-top image; b) 3D reconstruction

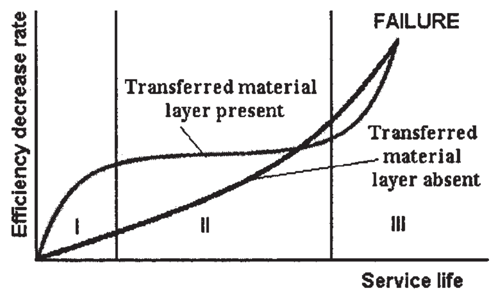


Fig. 11. Stages of transferred material layer influence on efficiency decreasing rate: I – layer appearance; II – layer compensation of wear; III – incapacity of layer to compensate the wear

this case silica. The particles detached from lip remain enclosed into film material and, as long as they are not bigger than the layer thickness, they do not affect the rod surface. In the 3D reconstruction presented in figure 10 can be observed a single silica particle embedded into transferred material, having the height less than layer thickness.

Another source for hard debris is the lip material. Due to long exposure to high local flashing temperatures and cyclic movements, the rubber is aging, becomes rigid and it is detached as hard particles. All these debris, if are not embedded into the transferred material film, perform an abrasive action on the rod surface.

The third stage of seal working life (fig.4c) is started when the transferred layer loses its continuity, large ruptures appearing. The cause is the size of hard particles: these one became thicker than the material layer by aggregating new debris, reach to the rod and lip surfaces, generate deep abrasion scars acting as "cutters" for the transferred layer. On the other hand, the adhesion wear is always acting (even the wear rate is slower due to the transferred material layer), leading to continuously increasing of the annulus between the rod and lip. As consequence, the layer is “extruded” by the air pressure from the sealing area, leading to the discontinuities.

At high sliding speed, in PEEK case, instead of the rod melting deformation, the friction generated heat leads to a rubber lip over-vulcanization phenomenon. The effects are: the elasticity loss of the lip, the detachment of the lip worn material as hard particles (instead of adhesion film forming) [11,12], and, as consequence, the catastrophic lip wear, (fig.8b).

The absence of the lubricant means the loss of the sealing effect due to the hydrodynamic film between lip and rod. The transferred material is more viscous than regular lubricants and provides a thicker layer; the sealing efficiency is improved this way for higher lip wear rates. In the absence of lubricant the wear of the sealing system, visible as efficiency decreasing rate, have a quasi-linear evolution, without a stabilized plateau. In case of transferred material layer developing, because of its compensatory effect, the efficiency loss evolution, (fig.11), presents a three shaped aspect [12].

Conclusions

Taking into account the above presented, following conclusion can be drawn:

- the pneumatic drives rods working in dry friction condition can be made by polymeric materials;
- the appropriate selection of the materials, according mainly to the sliding speed, can provide some advantages comparing to the metallic materials, i.e. a more efficient sealing due to the lip material transfer film;
- the formation of transferred material film is conditioned by thermal regime into the sealing area;
- the tribology and efficiency of the pneumatic drives' sealing systems working in dry conditions can be improved by the appropriate rods polymeric material selection, following the sliding speed;
- the use of polymeric materials for pneumatic drives rods is the best option when low inertia forces are required or metallic materials and lubricants are not allowed.

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