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## EXPERIMENTAL STUDY ON THE TRIBOLOGICAL BEHAVIOUR OF HOMOKINETIC COUPLING

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**Abstract:** Cycloidal pin-type gear reducers are classified within the domain of mechanical transmissions characterized by high transmission ratios, capable of transmitting torque values up to approximately 55,000 Nm. The main components of these reducers are the cycloidal gear and the homokinetic coupling, the latter of which is responsible for receiving and transmitting motion. This paper presents studies focused on the experimental determination of the friction coefficient and specific wear intensity, examining four pairs of materials and a lubricant utilized in mechanical transmissions. Based on the experimental data obtained, conclusions were drawn regarding the optimal material-lubricant combination that ensures high durability for these gears while simultaneously minimizing losses due to specific friction.

**Key words:** cycloidal pin-type gear, homokinetic coupling, wear intensity, friction coefficient, coupling.

### 1. INTRODUCTION

Cycloidal pin-type reducers are distinguished by their extensive range of mechanical applications, spanning from traditional technological machinery to contemporary systems featuring digitalized robotization. Their utilization across such diverse domains is attributed to their exceptional performance [1] which includes transmission ratios within a significant range ( $i = 9 \dots 428,485$ ), high efficiency, such as  $\eta = 0.95 \div 0.98$  for single-stage reducers,  $\eta = 0.85 \div 0.92$  for two-stage reducers and  $\eta \cong 0.75$  for three-stage reducers, and compact designs. These notable performances are associated with a low level of friction. However, prolonged use and high operating speeds result in gradual, significant wear ultimately leading to system failure [2].

Pin-type cycloidal reducers contain several tribological couplings characterized by linear contact, as classified under the second category of tribological contact classification, which includes both external and internal interactions. These couplings can be grouped as follows:

- the **pin-roller-tooth** coupling with a cycloidal tooth profile, representing the cycloidal gear engagement;

- the **pin-roller-bore** coupling located within the satellite disc, corresponding to the transverse homokinetic coupling;
- and the **central bearing** of the satellite.

The design of these couplings is crucial for the longevity of pin-type cycloidal reducers. While the design of the homokinetic coupling and the selection of the central bearing consider bending and contact stresses, tribological effects are often afforded less consideration. In the context of sustainable design, it is essential to examine the tribological behavior of the materials used in these gear reducers to extend the lifespan of mechanical assemblies [3].

Wear of the cycloidal gears results from cumulative processes caused by mechanical, tribological, and thermal phenomena. This study aims to determine the influence of tribological processes on durability, with a particular focus on the typical operational lifespan of paired elements characteristic of the homokinetic coupling.

The components of the cycloidal gear, which include the pins, the rollers affixed to them, and the cycloidal teeth, are designed with hardness values exceeding 58 HRC, resulting in minimal wear. Consequently, any failure is expected to occur only under accidental conditions [2].

Thus, the decommissioning of the pin-type cycloidal reducer couples occurs in a staged process, starting with the central bearing, followed by the homokinetic coupling, with the cycloidal gear itself being the most durable component.

Previous research was focused on the primary pair, specifically the most stressed component, which comprises the cycloidal disc interacting with the pins of the cycloidal drive. To gain a more comprehensive understanding of the wear phenomenon and to elucidate this process, the current article will examine the friction-wear mechanisms of the homokinetic coupling.

## 2. DESIGN FEATURES AND FUNCTIONAL ROLE OF THE HOMOKINETIC COUPLING

The cycloidal reducer is a special planetary mechanism designed to transform the rotational motion of the input shaft into a slower rotation with increased torque at the output shaft, through an eccentric cycloidal disc. The homokinetic cross coupling functions by capturing the rotational motion of the two diametrically opposed satellites and transmitting it to the output shaft.

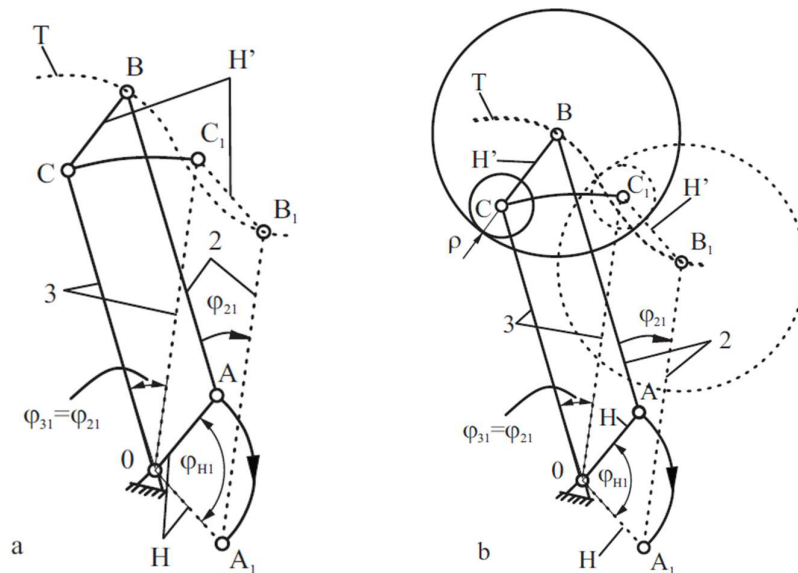
The functional-constructive principle (figure 1.a) and the kinematics of the homokinetic coupling (figure 1.b) are presented in figure 1,

both based on the H2H'3 parallelogram mechanism (handle **H**, 2 denotes the satellite with the cycloidal profile, and **H'** and **3** constitute the other sides of the parallelogram).

The rotational motion of the input shaft of the reducer is transmitted to element **H** (an eccentric mounted on the shaft) and subsequently to satellite **2**, which drives the output shaft. The motion is transmitted from element **2** to element **3** through the direct contact of pin **C** of the coupling with the bore machined in the satellite wheel. The main advantage of this type of reducer is its capacity for numerous simultaneous contacts, facilitating uniform load distribution. However, the contact pressure within the coupling areas remains elevated, resulting in severe tribological conditions in where wear and friction become critical processes [4].

To optimize the performance of pin-type cycloidal reducers, it is necessary to maintain a minimum level of hardness and friction on the contact surfaces, in addition to selecting an optimal material-lubricant combination.

The efficiency of pin-type cycloidal reducers [5] is determined by the specific instantaneous power loss ( $\psi$ ), influenced by the total friction coefficient of the reducer's couplings (the cycloidal gear, the homokinetic cross coupling, and the satellite's central bearing).



**Fig. 1.** Functional and structural concept (a) of the homokinetic coupling (b) [2]

The definition of the specific power loss in the homokinetic coupling is defined as the ratio of the power consumed due to friction to the active power associated with the satellite. This is determined using the following relation:

$$\psi_c = \frac{4 \cdot A \cdot \mu_c}{\pi \cdot R_c} \quad (1)$$

where:  $\mu_c$  – the global friction coefficient of the coupling;

$A$  – center distance or eccentricity (of the handle **H**);

$R_c$  – equidistant disposal radius of the coupling pins.

The global friction coefficient quantifies the effect of friction occurring between the component pairs of the homokinetic coupling, specifically the pin-roller pair and the roller-satellite bore, as illustrated in figure 2.

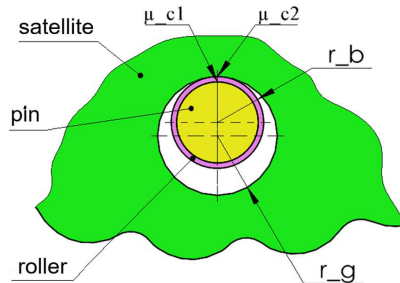


Fig. 2. The pin-roller and roller-bore couplings [2]

In studies [6][7], an analysis was performed to examine the impact of loading (contact pressure) on the friction and wear mechanisms of the main friction pairs in cycloidal pin-type gear reducers. Study [8] presents the findings of experimental investigations into the variation of the friction coefficient characteristic to pin-type cycloidal gears couplings. This variation is analyzed in relation to factors such as load, hardness, viscosity, roughness, speed, and the curvature radius of the cycloidal profile of the satellite.

Based on experimentally obtained data, statistically processed, a regression equation of the friction coefficient was established. This equation also highlights the degree of influence exerted by the parameters considered.

The necessity of analyzing the impact of loading (contact pressure) on the friction and

wear processes specific to the primary pairs of pin-type cycloidal reducers has been demonstrated [7-14].

### 3. EXPERIMENTAL INVESTIGATIONS

Reducing wear in the cycloidal gear depends on three essential factors: the choice of materials, the quality of surface finish, and maintaining a stable lubricant film. This study concentrates on the first factor, focusing on the performance of materials under controlled tribological stress conditions.

The main objective of this study was to experimentally determine the wear intensity and friction coefficient depending on the commonly associated with commonly utilized materials and lubricants specific to the homokinetic coupling.

The findings provide a foundation for recommendations regarding the selection of the optimal material-lubricant pair for the homokinetic coupling elements (pin, roller, cycloidal disc). This selection aims to minimize friction losses and enhance the durability of these components.

The experimental investigations focused on the pin-roller pair, which presents limitations from a tribological standpoint, characterized by linear contact with inner tangency, relative sliding motion and challenging lubrication conditions, in contrast to the pair in the cycloidal gear.

The designed and manufactured coupling elements were tailored to align with the specific contact geometry conditions characteristic of homokinetic couplings, for the cycloidal reducer type 8 as detailed in Table 1.

Table 1

The structural characteristics of the homokinetic coupling (cycloidal reducer type 8).

Parameter	Value
Transmitted torque (Nm)	2700
Number of pins	10
Eccentricity $A_c$ (mm)	13
Satellite width (mm)	10
Bore diameter of the satellite disc (mm)	57
Pin diameter (mm)	25
Maximum pin load (N)	6970
External stress $\sigma_k$ (MPa)	1670
Internal stress $\sigma_k$ (MPa)	1000

The experimental evaluation was carried out on the modeled coupling, mounted into the structure of a modified *Timken* tribological testing apparatus, as illustrated in Figure 3.

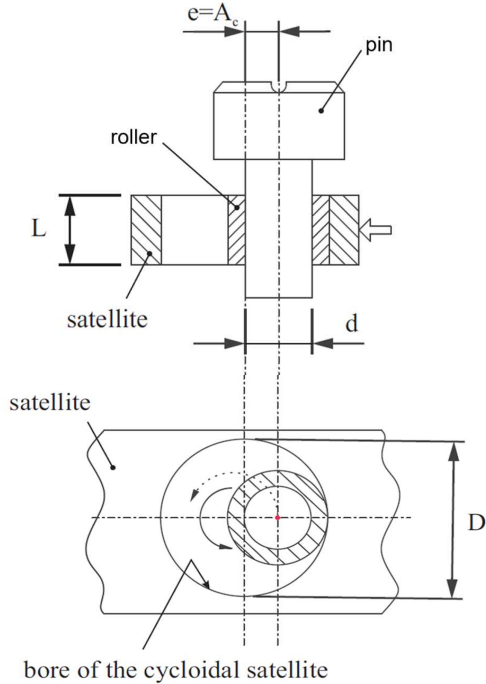


Fig. 3. Experimental friction homokinetic coupling (pin-roller and roller-bore) [2]

The device consists of a rotating shaft upon which the pin-roller assembly is mounted. This assembly executes a planetary motion within the bore of the satellite with a cycloidal profile, to which load  $N$  is applied.

The tests conducted to determine the wear coefficients specific to the materials pairs were performed under the conditions outlined in Table 2.

Table 2

Testing conditions on the Timken stand.	
Test condition	Value
Contact stress	$\sigma_k = 1000$ (MPa)
Pin rotational speed	$n = 1450 \pm 50$ (rot/min)
Timpul de testare	$t = 60 \pm 5$ (min)
Lubricant uniform applied	TIN 125 EP2
Pin material	Rul 1
Roller materials	MoMnCr 12, TiMnCr 12, 38 MoCrAl 09
Specimen hardness	58÷63 HRC
Suprfaces roughness of contact specimen	$R_a = 1.6$ ( $\mu\text{m}$ )

For each test specimen, with the roll mounted on the pin, the thickness of the worn material ( $h_m$ ) was measured at the contact surface. Subsequently, the corresponding wear coefficient was calculated using the following equation:

$$K_u = \frac{h_m}{\sigma_k \cdot L_f} \left[ \frac{\text{mm}^2}{N} \right] \quad (2)$$

where:  $L_f$  represents the length of the friction path.

Considering the local contact conditions of the homokinetic coupling components, this study conducted an evaluation of the material-lubricant pair's performance by analyzing how variations in normal loads influence the friction coefficient and wear intensity at the contact interface.

#### 4. RESULTS AND EVALUATION

The results of the experimental determinations regarding the establishment of the optimal material-lubricant pair are presented in Table 3 and Table 4.

Table 3

Experimentally determined wear coefficients [ $K_u \cdot 10^{-7}$ ] [ $\text{mm}^2/\text{N}$ ].

Roller material	Pin materia;			
	Rul 1	MoMnCr 12	TiMnCr 12	38 MoCrAl 09
Rul 1	1.6	9.5 / 0.7	7.0 / 1.0	4.8 / 1.1
MoMnCr 12	0.9 / 9.1	6.3	3.0 / 6.7	2.6 / 7.7
TiMnCr 12	1.0 / 6.4	7.0 / 2.6	4.9	3.8 / 6.1
38 MoCrAl 09	1.1 / 4.5	8.6 / 1.8	4.2 / 3.0	2.9

Pairs of identical materials are characterized by a singular wear coefficient value, whereas other material combinations exhibit two distinct values: the first representing the wear coefficient specific to the material constituting the pin, and the second pertains to the wear coefficient of the roller material (Table 3). Consequently, each material is characterized in terms of wear intensity both in self-combination and in conjunction with other materials.

In the characterization of the material pair, a global wear coefficient ( $K_{ue}$ ) is considered, defined in this context as the sum of the wear coefficients of each constituent material. This global wear coefficient serves as a basis to establish a ranking for the optimal material combination, which corresponds to the minimal wear of the pair and, respectively, its maximum durability (table 4).

Table 4

Experimentally determined global wear coefficients.

Pair number	Global wear coefficient, $K_{ue} \cdot 10^{-7}$ [ $\text{mm}^2/\text{N}$ ]	Pin material / Roller material
1	3.2	Rul 1 / Rul 1
2	5.6	Rul 1 / 38 MoCrAl 09
3	5.8	38 MoCrAl 09 / 38 MoCrAl 09
4	5.9	38 MoCrAl 09 / Rul 1
5	7.2	TiMnCr 12 / 38 MoCrAl 09
6	7.4	Rul 1 / TiMnCr 12
7	8.2	TiMnCr 12 / Rul 1
8	9.6	MoMnCr 12 / TiMnCr 12
9	9.8	TiMnCr 12 / TiMnCr 12
10	9.9	38 MoCrAl 09 / TiMnCr 12
11	10.0	Rul 1 / MoMnCr 12
12	10.2	MoMnCr 12 / Rul 1
13	10.3	38 MoCrAl 09 / MoMnCr 12
14	10.4	MoMnCr 12 / MoCrAl 09
15	10.5	TiMnCr 12 / MoMnCr 12
16	12.6	MoMnCr 12 / MoMnCr 12

Figure 4 illustrates that experimental evaluations of the friction coefficient's variations [6-8] can effectively indicate changes in the wear coefficient.

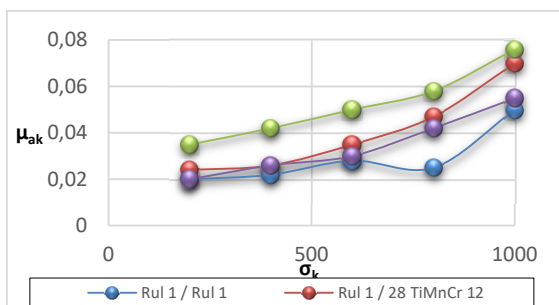


Fig. 4. Variation of the friction coefficient among the four material pairs when using TIN 125 EP2 oil

#### 4. CONCLUSIONS

The experimental data obtained were analyzed comparatively, leading to the

following conclusions regarding the assessment of the wear behavior of the tested material pairs:

- the specimen pair made of bearing steel demonstrates superior wear resistance in comparison to the other three analyzed steel pairs;
- identical material pairs, typically considered unfavorable in terms of adhesive wear due to the tendency to form welded junctions and exhibit similar deformation behavior, have showned different wear resistances depending upon the structure and properties of the surface layers;
- the optimal wear performance was observed for the combinations of Rul 1 and 38 MoCrAl 09 materials, both when evaluated individually and when paired with each other;
- the nitriding steel 38MoCrAl09 (subjected to nitriding in a gaseous medium, through a two-stage temperature process, with a layer depth 0.7 mm and a surface hardness of 1100 HV) demonstrates good wear resistance, confirming that the surface layers play an essential role in the complex phenomenon of friction and wear;
- increased wear resistance was noted for the material combination of TiMnCr 12 and 38 MoCrAl 09, with the former used for the pin and the latter for the roller, as well as for TiMnCr 12 with Rul 1 (regardless of whether they are used as pins or rollers);
- the use of bearing steel as a pin material resulted in the lowest wear levels;
- the MoMnCr 12 material showed a favorable behavior only when paired with the TiMnCr 12 material as the roller material;
- the data presented on the variation of the friction coefficient as a function of contact pressure for the analyzed material pairs are useful for quantifying the global friction coefficient of the homokinetic coupling (equation 1) and the specific power loss characteristic of this coupling.

The results obtained and analyzed allow the rational selection of material pairs for friction couplings characteristic of the pin-type cycloidal gears, ensuring their operation under optimal parameters with maximum durability.

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### Analiza experimentală a comportamentului tribologic al cuplelor homocinetice

**Abstract:** Reductoarele cicloidale cu bolțuri fac parte din categoria transmisiilor mecanice cu rapoarte mari de transmisie (cu valori ale momentelor transmise de aproape 55,000 Nm). Aceste reductoare au ca și componente principale angrenajul cicloidal și cuplajul homocinetic, acesta fiind cel care preia și transmite mișcarea. Studiile din această lucrare se focusează pe determinările experimentale a coeficientului de frecare și a intensității uzării specifice, cu considerarea a patru perechi de materiale și a unui lubrifiant utilizat pentru transmisiile mecanice. Pe baza datelor experimentale obținute au fost stabilite concluziile privind cuplul optim material-lubrifiant care asigură o durabilitate ridicată a acestor angrenaje și în același timp micșorează pierderile prin frecare specifică.

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