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RESEARCH

Analysis of Tribological Processes at Timing Belt's Tooth Flank

The paper presents basic tribomechanical systems in timing belt drives. Analysis of tribomechanical system belt's tooth - belt pulley's tooth, in which the largest value of friction force occurs, is conducted. Monitoring of tribological processes at the belt's tooth side is done according to previously established dynamics. Namely, testing of timing belt drive is performed on a specially designed test bench and measurement of tribological characteristics is performed by "TALYSURF 6" profiler. Analysis of tribological processes at the belt's tooth flank shows that roller and abrasion wear occur with consequential increase of belt's pitch. Wear leads to sudden decrease of service life and to failure of timing belt drive.

Keywords: *Timing belt drive, friction, wear, belt's pitch*

1. INTRODUCTION

Timing belt drives belong to the group of very young and insufficiently investigated drives. Considering their purpose and very important role in transmission of power and motion, it is necessary to adequately know tribological characteristics of timing belt drives.

Basic elements of the timing belt drive are belt pulleys and timing belt. Drive belt pulley drives the driven belt pulley through a tractive element, while the other branch is free.

In order to increase the service life and reliability of the timing belt drives, analysis of basic tribomechanical systems of the drive is performed, as well as the analysis of change of geometrical values during exploitation. At the same time, analysis of changes in topography of contact surfaces of the belt is conducted [1,2].

2. TRIBOMECHANICAL SYSTEMS IN TIMING BELT DRIVES

The largest amount of motion and power is transferred by shape, while only a small amount is transferred by friction. The influence of friction must not, by all means, be neglected. Appearance of friction in timing belt drives and its consequences have not been thoroughly explained. In contrast to other transmissions of power and motion (gears, chain drives, cardanic transmissions, etc.) in which friction mostly occurs in the contact of the two metal surfaces, in timing belt drives, there are one metal and one non-metal surface or two non-metal surfaces in the contact.

The basic tribomechanical systems in the timing belt drives are (Figure 1):

1. belt's tooth – belt pulley's tooth
2. belt's face - flange
3. the belt groove – apex of the belt pulley's tooth

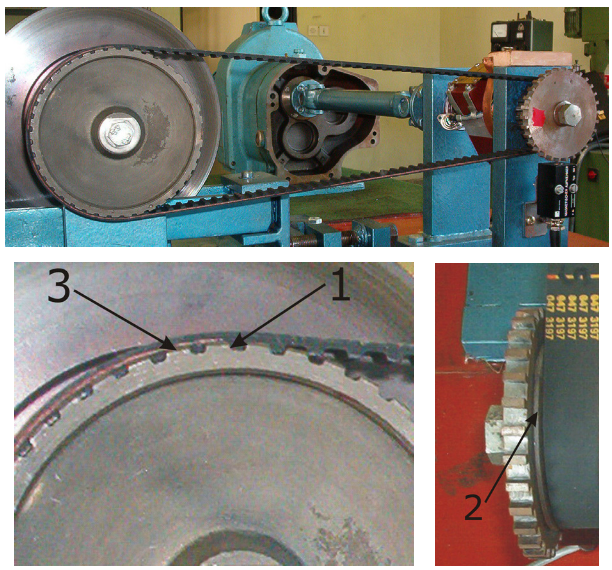

Figure 1. Timing belt drive and basic tribomechanical systems

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Types of motion that occur in these tribomechanical systems are given in Table 1.

Table 1. Tribomechanical systems and types of motion in timing belt drives

Tribomechanical system	Type of motion
belt's tooth – belt pulley's tooth	- impact - sliding - rolling
belt's face - flange	- impact - sliding
the belt groove– apex of the belt pulley's tooth	- sliding - rolling

The side surfaces of the belt's tooth and the belt pulley's tooth are in contact during the coupling. Firstly, line contact occurs at the point where the belt's tooth enters the coupling with the belt pulley. The coupling starts with the belt's tooth striking the belt pulley's tooth. The belt's tooth, considering its elastic properties, deforms and the contact surface increases. After the contact surface is increased and the belt and the belt pulley rotate, the belt's tooth starts to slide along the side surface of the belt pulley, during which the roll friction with sliding occurs [3-7].

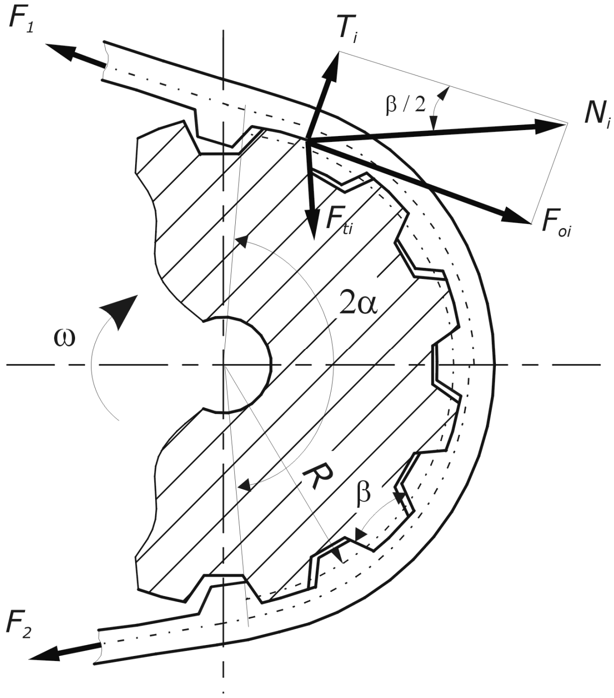

Figure 2. Friction force at the side surface of the belt's tooth

Value of the friction force increases with the increase of the length of the sliding path and achieves its greatest value at the root of the belt's tooth (Figure 2). At the same time, the action point of the resultant component of normal force moves from the tooth's apex towards its root. The normal force changes according to parabolic law:

$$N_i = -\frac{N_{\max}}{l_t^2} \cdot \left(l - l_t\right)^2 + N_{\max} \tag{1}$$

where:

$N_{\max}$ is maximal value of normal force ($N_{\max} \approx 1.5 F_0 / z_{01}$) and

l_t is the length of friction path.

The friction force occurs at the side surface of the belt's tooth and its value is determined according to the following expression:

$$F_{ti} = N_i \cdot \mu = \frac{F_{oi} \cdot \mu}{\cos(\beta/2)} \tag{2}$$

where:

N_i is normal force acting on the belt's tooth,

μ is the friction coefficient,

F_{oi} is circumferential force acting on the belt's tooth and

β is the angle of the belt's profile.

3. TESTING OF TIMING BELT DRIVE

Testing of timing belt drive is conducted on a test bench designed on purpose and made at the Laboratory for mechanical constructions an mechanization of the Faculty of mechanical engineering from Kragujevac. Test bench operates on a principle of opened loop power.

Basic elements of the test bench are:

1. drive unit (electric motor),
2. cardanic drive,
3. measuring (input) shaft,
4. input shaft's rotational speed transducer,
5. input shaft's torque transducer,
6. tested drive (timing belt drive),
7. output shaft,
8. mechanical brake,
9. tension mechanism and
10. amplifier bridge.

Figure 3 shows the test bench with basic elements. Mechanical brake provides a given amount of brake torque that is load torque on output shaft of the timing belt drive. Value of the load torque is obtained by readout of a display of digital amplifier bridge which obtains the torque signal from a measuring shaft, through signal preamplifier HBM EV2510A. Rotational speed of input shaft is also read on the amplifier bridge which obtains the signal through inductive sensor and impulse signal receiver of number of revolutions, HBM DV2556. Thus, regime at the input shaft of the driver is defined.

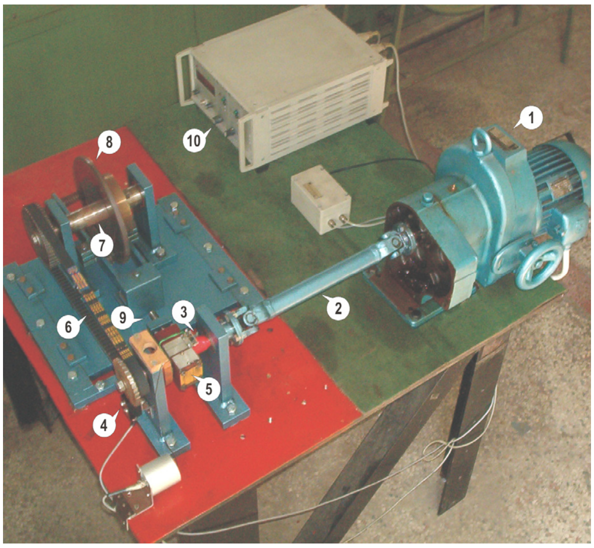

Figure 3. Test bench for testing of timing belt

In order to obtain a true picture on tribological characteristics of the timing belt, measurement of roughness parameters and determination of geometrical values are conducted. Measurement of these values is conducted according to previously determined dynamics.

Before the tests began, the state of the contact surfaces and initial values of the belt's geometrical values were established. Further measurements were conducted after a certain operation time and are shown in Table 2.

Table 2. Time intervals of measurement of roughness parameters and belt's geometrical values

Number of measurement	1	2	3	4	5	6	7	8	9	10
Operation time [h]	0	5	10	20	50	100	150	200	250	300

4. ROUGHNESS PARAMETERS MEASUREMENT

In addition to measurement of geometrical values, measurement of roughness parameters is conducted during testing of the timing belt. Considering the available measuring equipment (TALYSURF 6 - Figure 4) and corresponding software, curves of wear are designed and appearance of surfaces for four belt's teeth is given.

Figure 4. TALYSURF 6 profiler

The following roughness parameters are especially interesting for further analysis:

R_a - mean arithmetic deviation of profile from midline of the profile and

R_{max} - maximal height of roughness along reference length.

Measurement of roughness parameters is performed on three measuring points (Figure 5):

- at the apex of the belt's tooth - 1,
- at the flank of the belt's tooth - 2 and
- at the space between belt's teeth - 3.

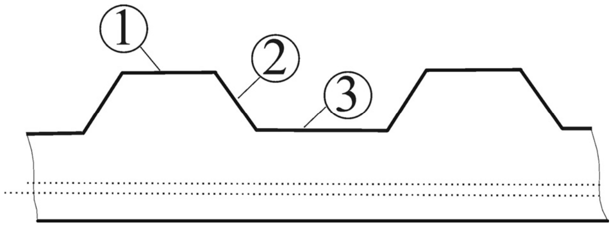

Figure 5. Measuring points on the belt for measurement of roughness parameters

Measurement of roughness parameters on the flank of the belt's tooth was conducted before the device started to operate and during the testing, according to previously determined dynamics. Measurements were conducted on four teeth. Results obtained by measurement are given in Table 3 and Figures 6 and 7.

For better clearness of the graphics, without a change of the analysis essence, the results for two belt's teeth are presented in the following table and diagrams. The results obtained for other two teeth are quite close to given values. This match of the results meets the expected image of tribological processes on contact surfaces of the belt's teeth. Similar dependence of the measured tribological values on time is gained at the flank of the tooth and at the space between teeth of the belt.

Table 3. Roughness parameters (R_a, R_{max}) at the flank of the belt's tooth

Belt tooth	Roughness parameter	Operation time (h)									
		0	5	10	20	50	100	150	200	250	300
1	R_a $[\mu m]$	9.33	11.2	8.9	8.3	11.57	9.0	9.2	6.4	5.0	4.8
	$R_{\max}$ $[\mu m]$	74.6	69	80	72	86.4	75	64	41	35	32
2	R_a $[\mu m]$	12.42	6.9	11.6	6.6	8.7	10.8	7.9	7.0	4.7	4.4
	$R_{\max}$ $[\mu m]$	105.9	58	93	69	67.4	68	57	41	40	35

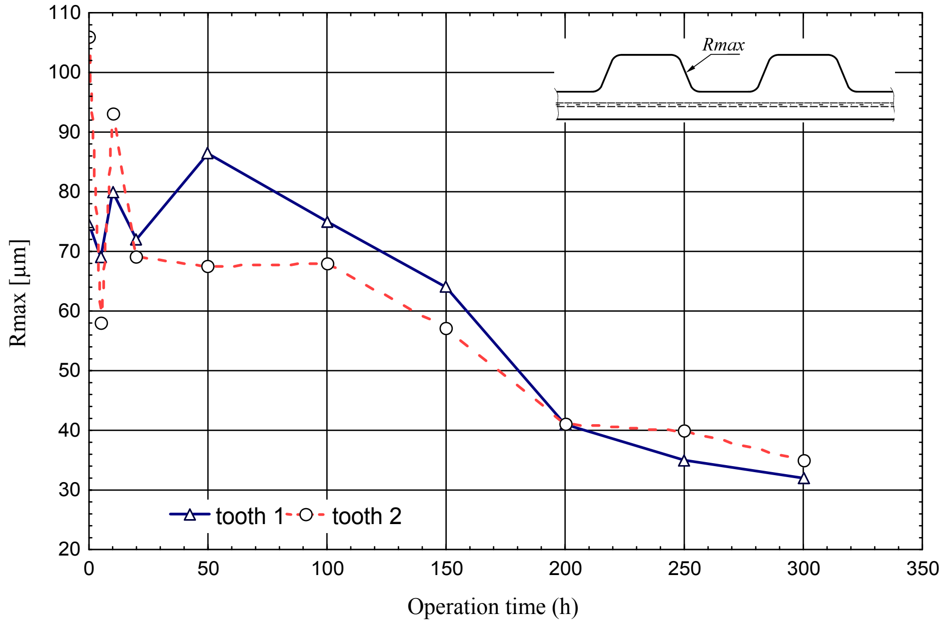

Figure 6. Change of R_{max} at the flank of the belt's tooth during operation

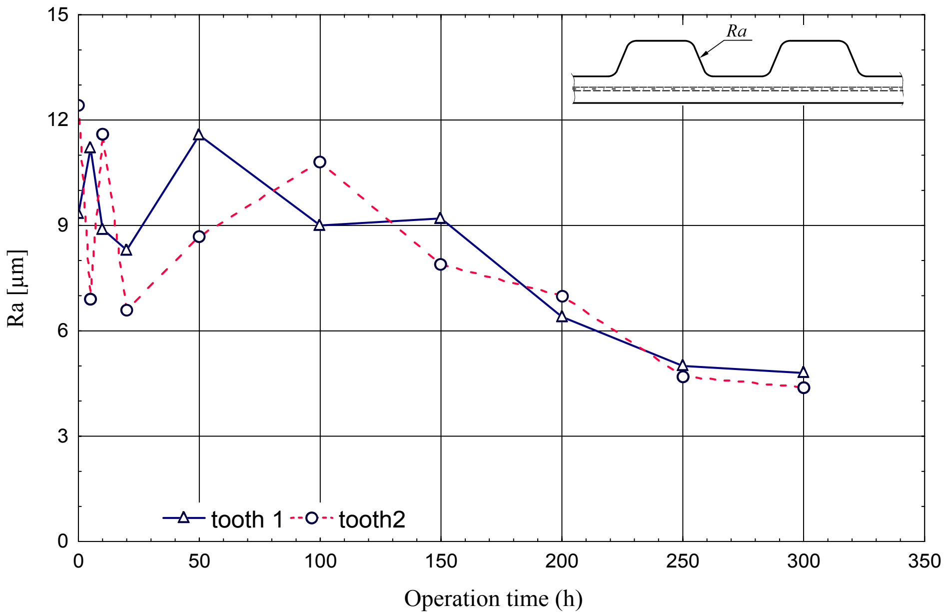

Figure 7. Change of R_a at the flank of the belt's tooth during operation

5. ANALYSIS OF OBTAINED RESULTS

By monitoring the roughness parameters in the period of working out, their decrease after 5 hours of operation may be noticed. Then topography is changed due to transition from technological to exploitation topography. Already in the next phase of the period of working out (5 to 10 hours of operation), monitored roughness parameters increase. In the first 5 hours of operation, the highest roughness peaks are being flattened, so the profile gets more even. However, in the next 5 hours, roller wear already occurs, that is rollers at the belt's tooth are generated. Part of material leaves the belt and then topology of the contact surface is changed, that is roughness parameters grow. Due to this specific form of wear that is characteristic for non-metals, roughness parameters have stochastic variation all the time.

Roller wear appears in conditions of high friction coefficient between polymers and metals and small tensile hardness of polymers. Mechanism of appearance of rollers as main cause for occurrence of roller wear is very specific (Figure 8). Variation of rollers cross-section size is important in the process of roller forming. Roller's cross-section value depends on material's tearing resistance, speed of relative motion, normal force and friction coefficient.

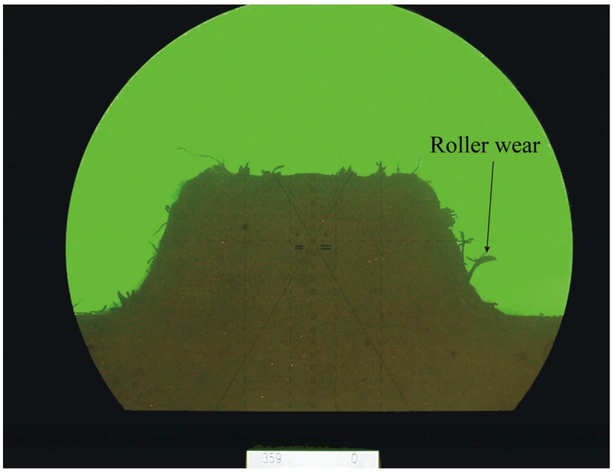

Figure 8. Roller wear of the belt's tooth

Due to its stochastic variation, it is impossible to establish the dependence between roughness parameter variations in the period of normal wear. Relief of the tooth's surface at the apex, at the flanks and at the space between teeth changes all the time, due to roller and abrasive wear. It is especially distinguished here, because the belt's material is rubber, much softer than belt pulley's material. But it may be noticed that topography changes the most at the flank of the belt's tooth, then at the apex of the belt's tooth and at least at the space between teeth. This variation is obvious and coincides with the analysis of corresponding tribomechanical systems at the belt drives.

Analysis of the obtained results shows that phenomenon of roller wear is especially present at the flanks and at the apex of the timing belt. Roller wear of the tooth's flank is greater than roller wear at the apex due to specialized tribomechanical system the belt's tooth - the belt pulley's tooth. Beginning of coupling between the belt's tooth and the belt pulley's tooth starts with the impact of the belt's tooth into the belt pulley's tooth. After that, belt's tooth slides along the side surface of the belt pulley's tooth and sliding friction with rolling occurs [10,12]. Value of the friction force is the greatest compared to friction forces in other tribomechanical systems. In addition to roller wear, abrasive wear also occurs in the timing belt. These two types of wear are dominant.

6. CONCLUSIONS

Basic tribomechanical systems in timing belt drives are: the belt' tooth - the belt pulley's tooth, belt's face - flange, the belt groove– apex of the belt pulley's tooth. Analysis of these tribomechanical systems shows that the influence of the friction forces that occur in them is not negligible, but directly influences transmission of power and motion and the drive's service life.

Values of the friction force are different in all three analyzed tribomechanical systems. The friction force has the greatest values at the side surface of the belt's tooth and the belt pulley's tooth. It has somewhat smaller values between the apex of the belt and the flange, while the smallest values of the friction force are found between the apex of the belt pulley's tooth and the space between the belt's teeth. Direction, course and intensity of these forces are directly connected to coupling kinematics of timing belt drives.

Occurrence of abrasive and roller wear is most apparent in timing belt. Abrasive wear occurs at the belt's face due to contact with the flange and at the belt's tooth apex due to contact with the pulley groove. Roller wear occurs at the flanks and apex of the belt's tooth which is in contact with the side surface of the belt pulley's tooth. Roller wear occurs in the period of working out and in the period of normal wear.

Due to roller wear of the side surfaces of the teeth and plastic deformations of the belt, the belt's pitch increases. Participation of roller wear in total extension of the belt increases with the increase of operation time of the timing belt because plastic deformations are the most distinguished in the period of working out. Variation of the belt's pitch leads to disturbance in operation of timing belt drives. Namely, variations of load distribution, decrease of carrying capacity and unevenness in operation occur. There raises a need for additional tensioning of the belt, which directly influences the service life of the drive.

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REFERENCES

[1] S. Tanasijević: *Mechanical drives: chain drives, timing belt drives, cardanic drives* (in Serbian), Yugoslav tribological society, Faculty of mechanical engineering from Kragujevac, 1994

[2] B. Stojanović, N. Miloradović: *Development of timing belt drives*, Mobility and Vehicle Mechanics, Vol. 35, No. 2, pp. 29-34, 2009

[3] T. Johannesson, M. Distner: *Dynamic loading of synchronous belts*, ASME, J. Mech. Design Vol. 124, 79-85, 2002

[4] H. Peeken, F. Fischer, E. Frenken: *Transfer of forces in timing belt drives* (in German), Konstruktion, Vol. 41, pp. 183-190, 1989

[5] T. H. C. Childs, K. W. Dalgarno, M. H. Hojjati, M. J. Tutt, A. J. Day: *The meshing of timing belt teeth in pulley grooves*. Proc. Instn Mech. Engrs, Part D: J. Automobile Engineering, Vol. 211, pp. 205-218, 1997

[6] T. H. C. Childs, K. W. Dalgarno, A. J. Day, R.B. Moore: *Automotive timing belt life laws and a user design guide*. Proc. Inst. Mech. Engrs, Part D: J. Automobile Engineering, Vol. 212, pp. 409-419, 1998

[7] N. Karolev, P. Gold: *Load distribution of timing belt drives transmitting variable torques*, Mech. Mach. Theory, Vol. 30, No.4, pp. 553-567, 1995

[8] S. Tanasijević: *Characteristics of Existence and Development of Machine Element Tribology*, Tribology in industry, Vol. 20, No 4, pp. 142-148, 1998

[9] S.Tanasijević: Tribology in design, Tribology in industry, No. 1, pp. 12-19, 1990

[10] B. Stojanović: *Characteristics of tribological processes in timing belts* (in Serbian), Master's thesis, Faculty of mechanical engineering from Kragujevac, 2007

[11] M. Babic, R. Ninkovic, S. Mitrovic, I. Bobic: *Influence of heat treatment on tribological behaviour of Zn-Al alloys*, Tribology in Industry, vol. 29, No. 1&2, pp. 23-31, 2007

[12] S. Tanasijević: *Tribologically correct design* (in Serbian), Faculty of mechanical engineering from Kragujevac, 2004