Journal of the Balkan Tribological Association *Vol. 21, No 3, 514–524* (*2015*)

Tribotechnics and tribomechanics

STATISTICAL ANALYSIS OF ROUGHNESS TIMING BELT IN OPERATION USING FULL FACTORIAL METHODS

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ABSTRACT

The changes of roughness parameters R_a and R_{tm} timing belt during the exploitation are shown in this work. The testing of timing belt was done on the measuring device constructed for that purpose at the Faculty of Engineering Sciences in Kragujevac. The testing was conducted on the basis of a predefined plan of the experiment. At the same time parameters of roughness on the apex of the belt tooth, in the space between belt teeth and on the flank of the belt tooth were monitored. Roughness measurements were carried out on a computer-assisted profilometer Talysurf 6. The analysis of change of roughness parameters was done using the full factorial method. The analysis of the results shows that the greatest impact on *R*a has the number of teeth of the timing belt, but on R_{tm} place where it was measured. There are also shown linear regression equations for the roughness parameters in the function of the effective parameters.

Keywords: roughness parameters, full factorial method, timing belt.

AIMS AND BACKGROUND

Timing belt transmitters are a relatively new concepts in transmission of power and motion. Toothed belt drive was first constructed in 1946 (Refs 1 and 2). It was a rubber belt with the trapezoidal tooth profile that was used as a carrier for sewing machines. Despite the benefits of the work, transmitters with the timing belt have just recently become widely used. Only after the timing belts were applied to the drive of the camshaft of internal combustion engine, did it become apparent how appropriate their usage was. The tightening up on the structural requirements in order to increase the working life and reduce the weight of a construction, initiated the appearance of a large number of testing timing belt drives.

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The testing of the tribological behaviour of a timing belt in operation shows that while working not only does the geometric size of the belt change but also the roughness of the contact surfaces. Changes in these values directly affect the working life of a belt timing drive, reducing its reliability and the degree of efficiency. Also, there is an increasing gap in contact, which directly leads to the distortion of contact geometry and appearance of vibration, noise, additional load bearing and reduction of the work capacity of belt timing drive.

The monitoring of the geometric and tribological sizes of the timing belt drive in the period of its exploitation provides an opportunity for predicting the failure and the extension of the life of the drive.

The tribological properties of the timing belt drive in the period of exploitation were analysed in this work. R_a and R_{tm} were monitored on certain teeth of the belt at regular intervals on the apex of the belt tooth, in the space between belt teeth and on the flank of the belt tooth. These three points are directly connected with the basic tribomechanical systems in timing belt drive. The kinematic analysis of coupling timing belt and pulley proves that the friction force appears in all three tribomechanical systems. Since the power transmission and motion of the timing belt drive is carried out by shape and friction, it is very important to monitor the tribological behaviour of the three contact surfaces 3–9.

The experiments in which the effects of more than one factor on response are investigated are known as full factorial experiments[10].

Full factorial experimental design technique was used to study the main effects and the interaction effects between observed parameters.

The aforementioned statistical method is used for processing experimental results, by applying the MINITAB 16. The applied factor experiment is 3^3, which has the three factors on the three levels, that is, a total of 27 combinations of the levels of factors. The lower level of the factor is denoted by 1, the basic level by 2 and the above by 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 and mechanisation of the Faculty of Mechanical Engineering from Kragujevac. Test bench operates on a principle of opened loop power[7,8,11].

Basic elements of the test bench are: 1 – drive unit (electric motor); 2 – cardanic drive; 3 – measuring (input) shaft; 4 – input shaft rotational speed transducer; 5 – input shaft torque transducer; 6 – tested drive (timing belt drive); 7 – output shaft; 8 – mechanical brake; 9 – tension mechanism; 10 – amplifier bridge.

Figure 1 shows the test bench with basic elements.

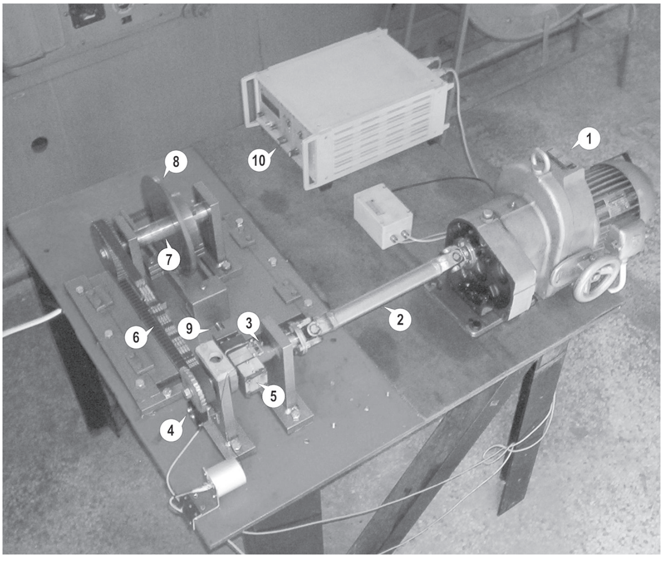


Fig. 1. Test bench for testing of timing belt

Input shaft torque ($M = 7.5$ Nm) and input shaft rotational speed ($n = 1400$ min^{-1}) were measured during the experiment. Tested timing belt has a trapezoidal tooth profile with pitch $p = 9.525$ mm. In order to obtain the most reliable and accurate results tests were performed on 5 timing belt of the same size and the same manufacturer. Values that are derived and analysed represent averaged values for all examined belts. Measurement of roughness parameters and geometric sizes was performed according to a predetermined schedule as on the belt as well as on belt pulley. Due to the difference in stiffness and material of the belt and belt pulley, changes in the measured sizes on belt pulley are insignificant relative to the belt and therefore not taken into account during an examination. In order to obtain a true picture on tribological characteristics of the timing belt, measurements of roughness parameters and determination of geometrical values are conducted.

PLAN OF EXPERIMENTS (FULL FACTORIAL DESIGN)

In engineering practice, an experiment is an everyday method of research or of performance of professional work. The factor experiment represents a statistical method of processing the experimental results when the subject of examination is influenced by several factors with multiple levels.

The experiments were conducted as per the full factorial design. The plan of the experiments involved analysing three parameters, all of parameters were of the third level. The three independent variables were the following: place on the tooth, the tooth and the time. The levels of the parameters are given in each array row, as shown in Table 1. The full factorial design is particularly useful in the

Table 1. Levels for various control factors

Control factors	Units	Level I	Level II	Level III
A: Place on the tooth	–	1	2	3
B: The tooth	–	1	2	3
C: The time	h	100	200	300

early stages of experimental work, especially when the number of process parameters or factors is less than or equals to 4. In the present investigation, full factorial arrays that had 27 rows and 3 columns were chosen, as shown in Table 2. In the full factorial design, the experimental results are shown for mean arithmetic deviation of profile from midline of the profile and for maximum height of roughness along reference length. The statistical analysis of variance is performed to observe which parameters are statistically significant. The optimum combination of the test parameters can be predicted.

Measurement of roughness is performed on three measuring points (place on the tooth), which are shown in Fig. 2.

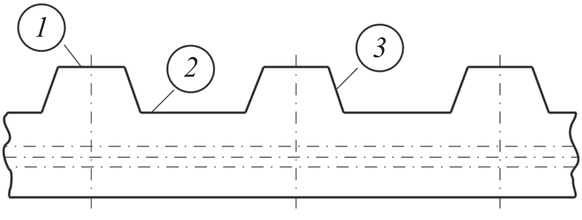


Fig. 2. Place on the tooth: *1* – at the apex of the belt tooth, *2* – at the space between belt teeth and *3* – at the flank of the belt tooth

RESULTS AND DISCUSSION

The experiments were conducted as per orthogonal array and mean arithmetic deviation of profile from midline of the profile and maximum height of roughness along reference length results obtained for various combinations of parameters are shown in Table 2. Analysis of the experimental values were carried out using MINITAB 16.

FULL FACTORIAL ANALYSIS

The influence of the control parameters such as place on the tooth, the tooth and the time on mean arithmetic deviation of profile from midline of the profile and maximum height of roughness along reference length has been evaluated using percentage contribution of factors and the Fischer allocation (F–allocation)[12–14].

Analysis of variance for R_a – mean arithmetic deviation of profile from midline of the profile, and R_{tm} – maximum height of roughness along reference length are given in Tables 3 and 4.

Table 2. Experimental design using L27 orthogonal array

L27	A – Place on the tooth	B – The tooth	C – The time (h)	R_a (μm)	R_{tm} (μm)
1	1	1	100	6.40	35.0
2	1	1	200	6.10	36.0
3	1	1	300	5.20	31.0
4	1	2	100	4.50	32.0
5	1	2	200	4.20	26.0
6	1	2	300	5.00	32.0
7	1	3	100	7.30	43.0
8	1	3	200	8.00	47.0
9	1	3	300	5.00	31.0
10	2	1	100	4.00	37.0
11	2	1	200	3.30	24.0
12	2	1	300	4.30	31.0
13	2	2	100	5.40	39.0
14	2	2	200	4.40	33.0
15	2	2	300	4.20	25.0
16	2	3	100	3.80	23.0
17	2	3	200	5.40	38.0
18	2	3	300	4.50	31.0
19	3	1	100	3.70	21.0
20	3	1	200	5.80	25.0
21	3	1	300	4.55	22.2
22	3	2	100	4.90	25.0
23	3	2	200	3.60	20.0
24	3	2	300	6.10	32.0
25	3	3	100	9.00	49.0
26	3	3	200	6.40	25.0
27	3	3	300	6.20	22.0

Table 3. Analysis of variance for R_a

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*	Pr
A	2	10.214	10.214	5.107	3.71	0.072	20.66
B	2	12.150	12.150	6.075	4.42	0.051	24.57
C	2	0.869	0.869	0.435	0.32	0.738	1.76
A*B	4	8.170	8.170	2.043	1.49	0.293	16.52
A*C	4	1.751	1.751	0.438	0.32	0.858	3.55
B*C	4	5.288	5.288	1.322	0.96	0.478	10.70
Error	8	11.003	11.003	1.375			22.25
Total	26	49.446					100.00

Table 4. Analysis of variance for R_{tm}

Source	DF	Seq SS	Adj SS	Adj MS	*F*	*P*	Pr
A	2	287.53	287.53	143.76	1.70	0.242	18.17
B	2	156.24	156.24	78.12	0.92	0.435	9.88
C	2	124.91	124.91	62.45	0.74	0.508	7.89
A*B	4	146.79	146.79	36.70	0.43	0.781	9.28
A*C	4	66.52	66.52	16.63	0.20	0.933	4.20
B*C	4	124.21	124.21	31.05	0.37	0.826	7.85
Error	8	676.12	676.12	84.51			42.73
Total	26	1582.32					100.00

Based on the percentage share for *R* factors (Table 3) it can be concluded that the greatest impact has the observed tooth with 24.57% and the place on the tooth with 20.66%, as well as their interaction (16.52%). While on R_{tm} (Table 4) the greatest impact has a place on the tooth with 18.17% and teeth with 9.88%, the significant influence also has their interaction with 9.28%.

Also the influence of factors can be determined by using the Fischer distribution for 99, 95 or 90% probability, based on the degree of freedom factor and the degree of freedom error. *F* values obtained by the analysis must be greater than the value of Fischer distribution for the appropriate number of the degrees of freedom. Based on the Fischer distribution for 90% probability ($F = 3.11$), it can be concluded that on the R_a the greatest impact have the place on the tooth and the tooth.

Figures 3 and 4 show the main effect plot for R_a – mean arithmetic deviation of profile from midline of the profile, and R_{tm} – maximum height of roughness along reference length, respectively.

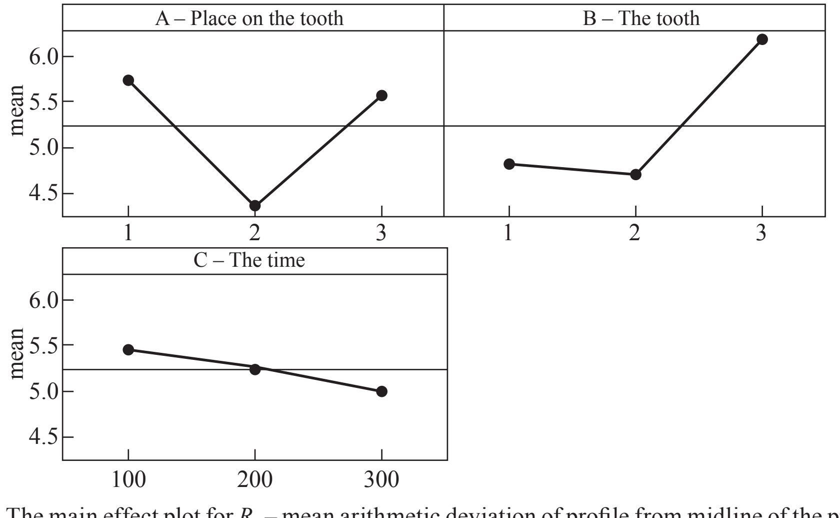


Fig. 3. The main effect plot for R_a – mean arithmetic deviation of profile from midline of the profile

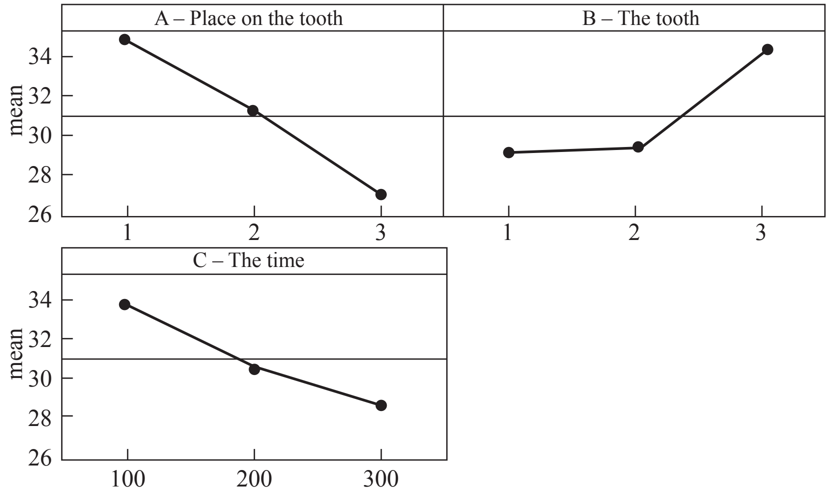


Fig. 4. The main effect plot for R_{tm} – maximum height of roughness along reference length

REGRESSION ANALYSIS

Mathematical models to predict mean arithmetic deviation of profile from midline of the profile and maximum height of roughness along reference length, respectively are formulated by response general regression analysis. This analysis gives wider insight to understand any problem in general, and to optimise the factors influencing the response in particular. Table 5 shows the results of response general regression analysis for R_a.

Table 6 shows the results of response general regression analysis for R_{tm}. The regression models in terms of coded values are represented by equations (1) and (2).

$$R_a = 4.47037 - 0.0805556A + 0.680556B - 0.00219444C \quad (1)$$

where $A = (a - 2)/1$, $B = (b - 2)/1$ and $C = (c - 200)/100$. A, B and C are coded values and a, b and c are actual values of factors.

Table 5. General regression analysis for R_a

Term	Coef.	SE Coef.	T	P
Constant	4.47037	1.10800	4.03463	0.001
A	–0.08056	0.31132	–0.25875	0.798
B	0.68056	0.31132	2.18602	0.039
C	–0.00219	0.00311	–0.70488	0.488

Table 6. General regression analysis for R_{tm}

Term	Coef.	SE Coef.	T	P
Constant	38.9111	5.67484	6.85677	0.000
A	–3.9889	1.59449	–2.50166	0.020
B	2.6000	1.59449	1.63061	0.117
C	–0.0260	0.01594	–1.63061	0.117

$$R_{tm} = 38.9111 - 3.98889A + 2.6B - 0.026C \tag{2}$$

where $A = (a - 2)/1$, $B = (b - 2)/1$ and $C = (c - 200)/100$. A, B and C are coded values and a, b and c are actual values of factors.

ANALYSIS CONTOUR AND SURFACE PLOTS

The contour plot of placed on the tooth versus tooth is given in Fig. 5. The curved contour lines is present due to interaction effect between these two factors. Based on Fig. 5, it can be seen that the minimum value of R_a is in the space between belt teeth (place of the tooth – 2) regardless of the tooth. Surface plots with mean arithmetic deviation of profile from midline of the profile as response is plotted for place on the tooth versus tooth as shown in Fig. 6. In this figure it is also visible

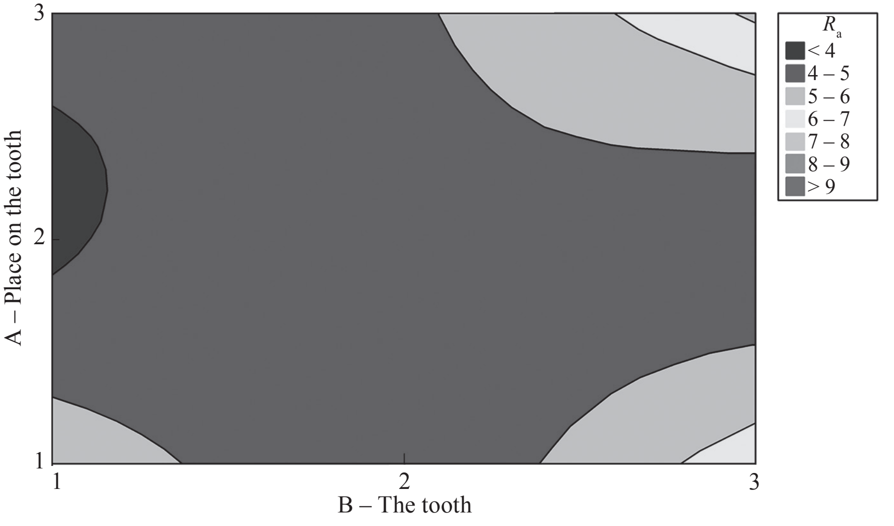
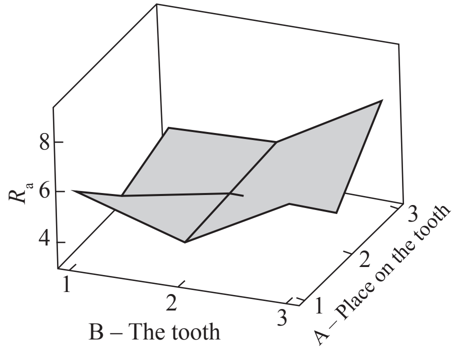


Fig. 5. Contour plot of R_a – mean arithmetic deviation of profile from midline of the profile depending on the factors A and B

Fig. 6. Surface plot of R_a – mean arithmetic deviation of profile from midline of the profile depending on the factors A and B



that the lowest value of R_a is in the space between the belt teeth on each observed tooth.

The contour plot for maximum height of roughness along reference length of placed on the tooth versus tooth is given in Fig. 7. The curved contour lines are present due to interaction effect between these two factors. Based on Fig. 7, it can be concluded that the minimum value R_{tm} (maximum height of roughness along reference length) is at the flank of the belt tooth on the observed tooth 1, while the highest value of the R_{tm} is in the flank of the belt tooth 3. Surface plots with maximum height of roughness along reference length as response is plotted for place on the tooth versus tooth as shown in Fig. 8.

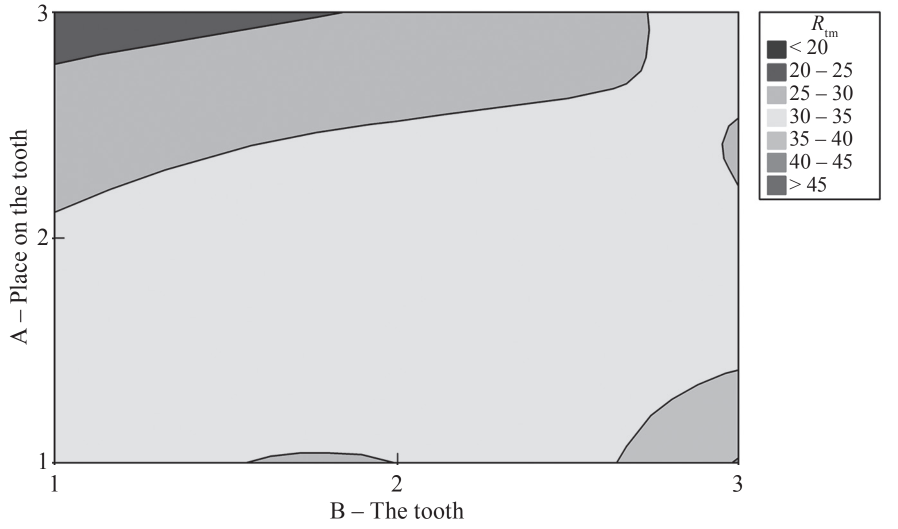


Fig. 7. Contour plot of R_{tm} – maximum height of roughness along reference length depending on the factors A and B

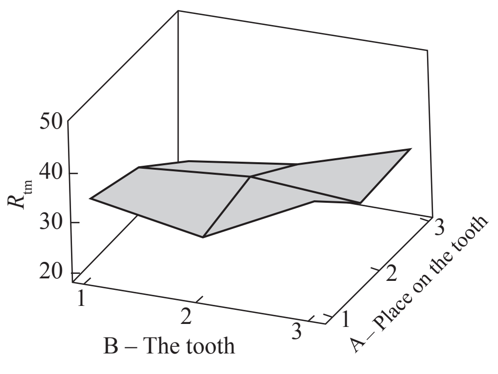


Fig. 8. Surface plot of R_{tm} – maximum height of roughness along reference length depending on the factors A and B

CONCLUSIONS

The transmission of power and motion for timing belt drive is performed by shape and friction. Friction leads to changes in the topography of the contact area, i.e. to the change in surface roughness. The changes in surface roughness in the running-in period are expected, since the topography of the contact surfaces is transferred from the technological one to topography of exploitation. These changes result from torque, ample power, initial tension, radial force, centrifugal force, the air, deformation of the belt due to bending and stretching, construction belts, traction element and belt pulley, precision fabrication and assembly, quality of processing of the contact surfaces, etc. That is, changes are in direct connection with kinematic timing belt transmissions. By monitoring the roughness parameters during the exploitation, it can be predicted the expected value in certain time interval, and so the occurrence of failures can be prevented.

The applied full factorial method shows the size of various parameters on the value of the roughness R_a and R_{tm}. The biggest influence on R_a has the number of teeth of the timing belt, but on R_{tm} place where it was measured. In order to monitor the parameters of roughness linear regression equations in the function of the parameters analysed are formulated. There are also presented the spatial dependent diagrams R_a and R_{tm} dependent on the position on the tooth and the number of teeth.

The minimum value of the mean arithmetic deviation of profile from midline of the profile is at the space between belt teeth on the all the analysed teeth, while the lowest value of the maximum height of roughness along the side of the reference length on the flank of the belt tooth on the observed tooth 1.

ACKNOWLEDGEMENTS

This paper presents the research results obtained within the framework of the projects TR-350 21 and TR-25041 financially supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

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Received 11 July 2014
Revised 19 December 2014