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Defining a theoretical model of wear - caused failure of tool machine elements

This paper considers production equipment failures caused by wear. A short overview is given on the results of statistically processed data on production equipment failures, gained by observing 20 representative and, from the point of view of failure frequency, problematic machine elements. The goal of this research is to detect the current equipment condition having in mind reliability and create a theoretical base for optimal renewal part stock planning.

Keywords: *failure, wear, production equipment, Poisson probability distribution, optimal renewal part stock planning.*

1. INTRODUCTION

Present day technical development has risen numerous questions concerning complex technical systems operation effectiveness. The basic demand imposed on a technical system is failure-free operation within a required period of time. The problem of reliability is one of the key problems of state-of-the-art tool machines, whether observed as a part of a complex production system or as an independent system. Current trends of tool machine development suggest an increase of automation level, performance improvement (load, operating temperature, pace), flexibility increase and size and mass decrease.

Elements reliability of a machine as a technical system is a probability that the system would successfully (with no failures) serve the purpose, i.e. objective function, within a certain period of time. Depending on a system characteristics and service conditions, in a broader sense reliability implies failure-free operation time, system element life cycle, overhaul convenience and system ability to maintain the quality indicators within the given limits. As both failure moment and failure-free operation period are random variable, reliability is in a considerable degree based on the probability theory and mathematical statistics, information theory, mass service theory, failure physics and other scientific fields. Evaluation of the attained reliability level and necessity for a continual reliability growth are also closely connected to economical criteria. They occur as basic criteria to be satisfied while solving numerous practical problems of reliability. Having these reasons in mind, optimal reliability values of both system elements and a system as a whole should be considered and defined through all phases of system projecting, production and service.

Tool machines are very complex technical systems whose reliability depends on a large number of elements, subassemblies and assemblies of very machines. The condition of both a machine (operating reliability) and the whole production system is largely defined by the intensity of complex processes of element friction and wear. It is not a rare case in metal-industry in Serbia that tool machine technical system maintenance is undertaken solely if the element/system condition requires it, where the system of preventive maintenance is not in operation. In certain enterprises there is neither a detailed record on equipment element failure nor renewal machine part optimal planning. This paper deals with such cases aiming to suggest possible ways of improving current conditions.

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2. FAILURE PHYSICS

Physics of tool machine tribomechanical system failures is a topical and at the same time very complex research field. Tool machines contain all types of tribomechanical systems, i.e. contact couples which are to be widely found in technical systems (Figure 1).

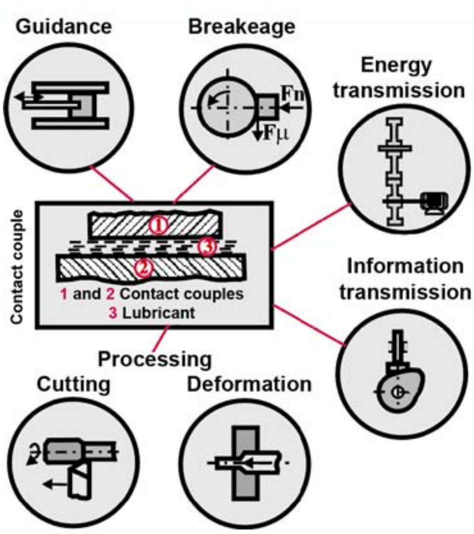

Figure 1. Technical system contact couples [4]

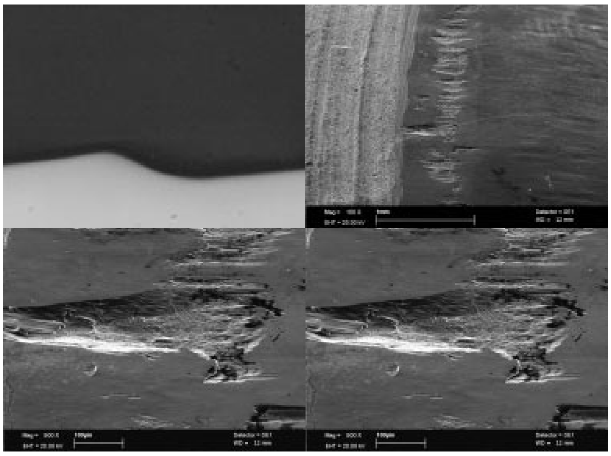

Figure 2. a) Section through tooth. Wear at start of active flank after 128 hours 100x magnification. Light part in figure is tooth, black is matrix substrate. b) SEM picture of damages at start of active flank. c) SEM picture of individual damage at root with striation marks. d) Crack surfacing, will form a metal flake and spall off. The crack can bee seen in the c) photo. 128 hours of running.

Machine element wear process development under very complex operating conditions disables continual observing and quantification of wear parameters of all characteristic machine elements, which consequently disables precise defining of preventive measures. For example, on a tool machine, it is very difficult to observe directly wear process development of a gear [3], grooved shaft as well as a vast number of other elements (Figure 2).

In order to increase the degree of reliability, industrial practice, as far as tool machines are concerned, recognizes a wide use of contemporary methods of technical diagnostics. Technical diagnostics implies a scientific technical field comprising theory, methods and tools for identification of technical system condition in terms of limited information. The primal aim of technical diagnostics is detecting and prevention of technical system potential failures. It is attained by measuring characteristic diagnostic parameters (vibration, temperature, product of wear in a lubricant). According to measured diagnostic parameters and determined criteria, a conclusion is drawn whether the measured parameters are within the acceptable limits [9]. One of the most suitable methods for failure analysis is FTA – Fault Tree Analysis. It is a deductive method often applied in diagnostics as it enables prediction of most possible failure causes. Failure tree construction aim is modelling conditions which lead to undesirable failure which is observed. It means that this procedure is used for analysis of both potential faults and their causes. The analysis begins with qualitative definition of an undesired event, and then, going through system configuration, by use of deduction system element failures are found as well as procedural errors which can lead to unwanted events [4]. Most often, failures occur as a consequence of lubricant degradation, improper lubrication, inadequate lubricant quality, the very mechanism of failure occurrance, error in design, error in element assembling. Causes and frequency of certain machine element failures are mostly connected with the very elements and their function within the machine [5, 6].

3. PLANNING RENEWAL PART STOCK

Stock could be seen as an absorber which eliminates/reduces disagreement between consumption of certain goods from the stock and its arrival into the warehouse. It would be ideal if the moment when the need arises would be the moment of goods arrival to a warehouse. However, this is impossible to achieve as there are numerous and at the same time hardly manageable necessary conditions. Some of them are an absolute correlation between stock and supply, an absolute reliability of all parts that make a production system, an absolute stability of all parameters that influence the need arisal for certain goods, parameters that influence supply, etc. As it is obvious that zero stock is impossible to achieve, logistics should make all possible efforts to ensure that money invested in making stock is used in the best way and thus contribute to the final goal of any enterprise, i.e. making the largest profit within certain constrains [2]. Figure 3 represents a stock costs graph [2].

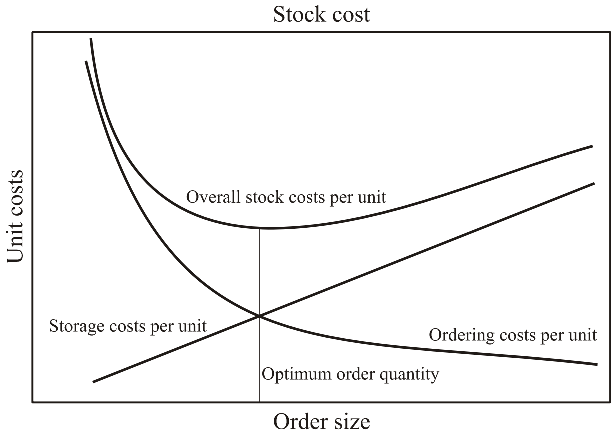

Figure 3. Stack costs graph [2]

For machine and equipment maintenance, having stock is a necessity, which would enable a prompt intervention of the maintenance team. Due to stochastic nature of failure occurrance, stock planning is an extremely complex process and it is essentially different from production material stock planning. When planning renewal part stock it is necessary to take into account each position of installing parts independently, then determine the expected number of failures (replacements) during planned period of time, and finally set up those values. This summative value represents a required number of monitored elements within a planned period of time. There are two additional items to be added to this value – the number of renewal parts to be used in preventive interventions as well as the number of parts used as contingency compensation.

A special problem of stock management, a frequent case of industrial practice in Serbia, is a low level of preventive maintenance and installation of non-original parts. The reasons of this case are of financial nature, but is a certain degree there is also no insight into possible negative circumstances (improper production, improper material choice, assembly errors, production of a part only after a failure, etc.). Another issue discussed in this paper is installation of one and the same renewal part into more machines with no precise record on either the machine where it is installed or the time of installation. Namely, the only data put on the record suggest that due to a failure a renewal part was installed on a certain day.

4. SAMPLE CHOICE

By observing renewal part failures in a medium-sized metal-industry enterprise the following was noted:

- high frequency failures occur on those parts that are as non original ones built in different machines,
- lack of evidence about the built-in parts relating an inventory number of the machine where the part was installed. For example, one and the same renewal part is built in more machines,
- extremely low level of preventive maintaining within the observed enterprise,
- a certain number of renewal parts are produced only after the failure, i.e. only when the need arises, which makes even bigger negative economic consequences.

Having all this in mind, the authors of this paper firstly systematized data about the most frequent part failures and suggested a theoretical model of failure possibility distribution. Besides, triboeconomical indicator of failure influence was given, having in mind the mean time of failure-free operation, renewal part production time and part replacement time for 20 representative parts. Results are given in Table 1.

Triboeconomic index (TEP) is evaluated according to the expression :

$$\mathrm{TEP} = \left[\left(\frac{T_{sr}}{T_{sr(max)}} \cdot \frac{Tiz(min)}{T_{iz}} \cdot \frac{T_{z(min)}}{Tz} \right]^{\frac{1}{3}}, \text{ where:}$$

T_{sr}, T_{iz}, T_z - are mean time of failure-free operation, production mean time and mean time of the observed part replacement, respectively. Index-min or index-max referred to the minimal, i.e. maximum values of the corresponding time in the entire population of the analyzed renewal parts.

Table 1.

No	Renewal part	Renewal part ptoduction time (h)	Part replacement time (h)	Mean time of failure-free operation (months)	Triboeconomic index (TEP)	Relation TEP/TEP max
1	Gear -1	10.0	8.0	1.46	0.157	0.166
2	Gear -2	9.00	16.0	4.73	0.191	0.202
3	Gear -3	8.00	16.0	2.92	0.083	0.088
4	Gear -4	5.00	12.0	1.90	0.188	0.200
5	Gear -5	12.0	12.0	2.66	0.157	0.167
6	Gear -6	5.50	8.0	1.60	0.197	0.209
7	Gear beam	12.0	10.0	2.95	0.173	0.184
8	Gear segment-1	6.0	16.0	3.12	0.190	0.201
9	Gear with shaft	7.0	20.0	3.17	0.168	0.179
10	Gear segment-2	6.0	16.0	2.18	0.168	0.179
11	Grooved bush	9.0	20.0	2.0	0.133	0.141
12	Grooved shaft	3.0	10.0	1.73	0.230	0.244
13	Lead screw-1	18.0	10.0	4.31	0.172	0.182
14	Lead screw -2	18.0	20.0	3.70	0.130	0.137
15	Lead screw -3	35.0	10.0	3.40	0.213	0.226
16	Lever-whisker-1	3.5	0.5	3.66	0.768	0.808
17	Lever-whisker -2	2.0	0.5	3.97	0.943	1.00
18	Right ball deflector	5.5	30.0	4.30	0.177	0.187
19	Left ball deflector	5.5	30.0	4.30	0.177	0.187
20	Five-pointed star	7.0	10.0	2.26	0.190	0.201

According to such a way of defining TEP, all observed parts are assorted into the lineup which theoretical maximum has a unit value. From the last two columns in Table 1 it can be noted that triboeconomical index values of most parts are rather low. This further means that the failure-caused economical consequences of the large number of observed parts are very negative. Diagram given in Figure 4 illustrates the distribution of the mean time failure-free operation for each and all of the 20 observed elements.

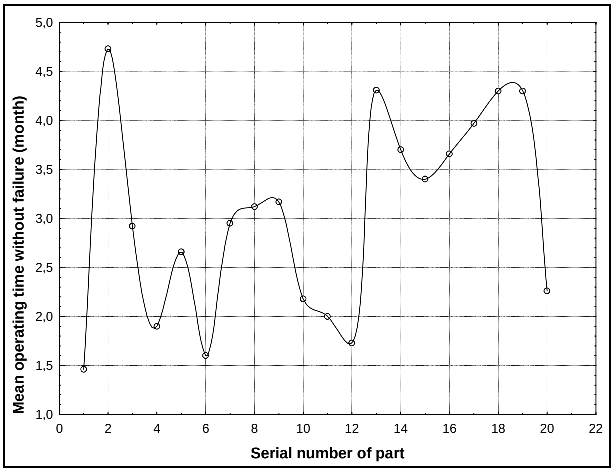

Figure 4. The distribution of the mean time failure-free operation for the 20 observed elements

5. THEORETICAL FOUNDATION OF THE PROPOSED MODEL

There are different theoretical models of technical systems to be found in reference [1]. After processing of a vast amount of data concerning production equipment failure, the authors of the paper have established that the production equipment failures conform to Poisson probability distribution.

In order to point out highly explicit analogy between Poisson process and the problem of observed production equipment failure, the basic assumptions of the Model [7] are given.

Poisson process considers the number of events (failures) in a period of time, where the probability of an event in a short time interval Δt is $\lambda \cdot \Delta t$, where λ is a constant. Mathematical definition of Poisson process implies the following supposiotions:

- the probability to pass from a condition characterized by (n) events (failures) to the condition of (n+1) events (failures), in period Δt is $\lambda \cdot \Delta t$. Parameter λ represents failure intensity and it is expressed in number of failures per second.

- events are interrelated, which is the case with the observed system,
- events are irreversible, which means that the number of events increases with time,
- probability of the occurrance of two or more events in a short time interval (Δt) is negligible.

If we seek for the probability of the event (n) occurrance at time t, a system of differential equations could be set up. Those equations represent the situation probability and transition probability. If the probability of n events which took place in time t is denoted P(X=n, t)=Pn(t), it becomes clear that the probability that no event took place in time $(t+\Delta t)$ would be equal to the product of probability that no event happened in time t and probability that no event happened in time Δt, i.e.:

$$Po(t+\Delta t)=(1-\lambda\cdot\Delta t)\cdot Po(t)\,.$$

A similar consideration can impose conclusion that an event in the time interval $(t+\Delta t)$ may occur in two different ways:

1) either there was no event in time Δt, so one event took place in time t, or

2) one event has already happened in time t, after which no event followed in time interval Δt. In mathematical terms:

$$P1(t+\Delta t)=Po(t)\cdot\lambda\cdot\Delta t+(1-\lambda\cdot\Delta t)\cdot P1(t).$$

Further consideration, which always keeps the analogy between an event (in terms of mathematics) and equipment element failure (in terms of physics), leads to Poisson law of probability distribution, i.e.:

$$P_n(\lambda)=\frac{(\lambda\cdot t)^n\cdot e^{-\lambda\cdot t}}{n!}\text{, where:}$$

$P_n(\lambda)$ – the probability of *'n'* failure occurrance;

λ – the failure intensity expressed in number of failures per second;

n – the number of failures.

6. THE CHECKOUT OF THE PROPOSED MODEL OF POISSON DISTRIBUTION FOR PREDICTING THE OBSERVED MACHINE PART FAILURES

It is confirmed that to predict the failure of any out of 20 mechanical elements of the considered system it would be sufficient to know the mean time of failure-free operation of elements within the whole operational system during the previous period of operation. As an example of result processing for lead screw the following values are systematized in Table 2:

a. time intervals between two failures (expressed in months),
b. estimated statistical probabilities (expressed in percentage),
c. probabilities estimated according to Poisson distribution, and
d. percentage differences between statistical probabilities and probabilities estimated by Poisson distribution.

As an example of duly correspondence between theoretical and statistical failure probability, data relevant to grooved shaft failure are given:

- failure intensity λ= 0.5770682 failures per month, and
- mean time of failure-free operation: T_{sr} = 1.732897 months, and
- correlation coefficient, R = 0.9947367, which in this particular case represents a volume of theoretical relation between mean time failure-free operation and failure probability estimated by Poisson distribution with respect to statistical, real probabilities.

Figure 5 represents the graph of cumulative distribution of statistical failure probabilities. It can be noted that failure intensities have almost linear alteration in three phases of failure-free operation time. However, regarding high correlation coefficients attained by comparing Poisson probability distribution to statistical probability distribution for all 20 considered parts it would be adequate to predict possible failures and plan renewal part stock on the basis of theoretical distribution, i.e. Poisson distribution of failure-free operation time.

***Table 2**. Failure probabilities*

Time interval (months)	Statistical probabilities of failures (%)	Failure probabilities according to Poisson process (%)	Probability differences (%)	Time interval (months)	Statistical probabilities of failures (%)	Failure probabilities according to Poisson process (%)	Probability differences (%)
0.0	0	0.0000	0.000	1.130	45	47.904	2.904
0.03	2	1.7160	0.284	1.131	48	47.934	0.066
0.10	5	56070	0.607	1.160	50	48.798	1.202
0.11	7	6.1500	0.850	1.360	52	54.379	2.379
0.12	10	6.6900	3.310	1.390	55	55.162	0.162
0.28	12	14.920	2.920	1.620	57	60.736	3.736
0.31	14	16.380	2.380	1.660	60	61.631	1.631
0.34	17	17.815	0.815	1.740	64	63.363	0.637
0.36	19	18.759	0.241	2.000	69	68.467	0.533
0.43	21	21.975	0.975	2.070	71	69.715	1.285
0.47	24	23.755	0.245	2.130	76	70.746	5.254
0.51	26	25.495	0.505	2.160	79	71.248	7.752
0.53	29	26.350	2.650	2.230	81	72.386	8.614
0.54	31	26.774	4.226	3.030	83	82.597	0.403
0.57	33	28.031	4.969	3.360	86	85.614	0.386
0.77	36	35.875	0.125	4.740	90	93.513	3.513
0.80	38	36.976	1.024	6.330	93	97.408	4.408
0.97	40	42.865	2.865	7.560	95	98.726	3.726
1.00	43	43.846	0.846	10.80	100	100.00	0.000

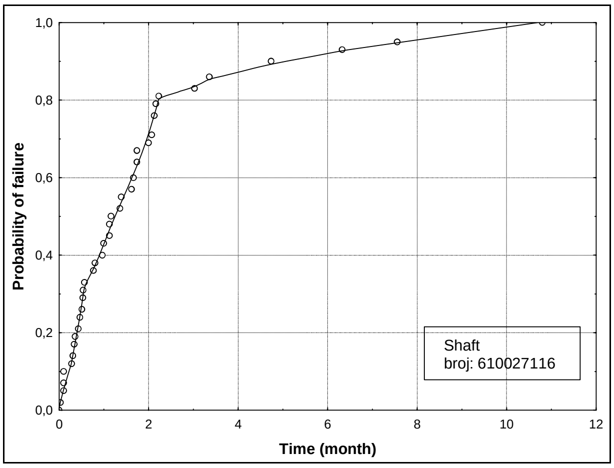

Figure 5. Cumulative distribution of statistical failure probabilities

7. CONCLUSION

The findings of the research can be stated as follows:

a. Planning renewal parts stock, where failures are the consequence of renewal parts wear, building-in non-original parts, and, basically, maintaining the equipment only when the need arises, is a very complex issue.

b. More precise renewal parts stock planning, within the considered enterprise, is in a certain degree aggravated due to building the same renewal parts in more machines, with no precise data on either machine inventory number or the precise moment of the renewal part installation or the exact machine where it was installed.

c. Reliability of the considered equipment elements is at a very low level. This is supported by the fact that according to the results of data processing during a week, a failure of at least one out of 20 considered elements is certain to happen.

d. In order to increase reliability and reduce negative failure consequences (producing the part only after the failure, building in the part only after the failure, etc.), we can use the suggested failure shift regularities, which principally conform to Poisson failure probability distribution, as a temporal solution before the preventive equipment maintenance system is introduced.

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