ANALYSIS OF THE DEPENDENCE OF SHAFT SAFETY FACTOR ON SURFACE HARDENING FACTOR Kv FOR THE CRITICAL SECTION WHERE THE SHAFT CHANGES DIAMETER

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Abstract: This paper presents the results of the study on the dependence of the shaft safety factor for the critical section where the shaft changes diameter. This critical section is common for most shafts that are often encountered in mechanical engineering, and it is known as a major source of stress concentration. The aim of this paper is to present the results of the dependence of the shaft safety factor Kv, as well as to test its affect on the amplitude of the fatigue strength of the mechanical part for the said critical section. The results are shown in the diagram, and the dependence in some cases is significant and very stochastic.

Key words: gerotor pumps, rotational elements, contact stresses, numerical analysis

1. INTRODUCTION

Shafts, as carriers of mechanical parts, are commonly calculated in accordance with the criteria of hardness and endurance. The calculation procedure was defined 14 years ago by DIN 743 standard. This standard defines procedures for calculation of dynamic and static shaft safety factor. The standard DIN 743 has been prepared by the German Institute for Standardization and Institute for Machine Elements and Machine Design of the Technical University of Dresden. [1]-[3].

The shafts are usually loaded with the alternate change of bending moment and torsional moment (figure 1). It means that the amplitude of the bending moment is equal to the total value of the bending moment, while the mean value of the bending moment is equal to zero. On the other hand, the amplitude of the torsional moment is equal to the mean value of the torsional moment, and these two values are equal to the half torque on the shaft [4].

This paper will consider the dynamic safety factor only. The figure 2. shows a flow diagram of calculation of dynamic shaft safety factor SD.

Where:
- K1 - is a technological factor of the influence delivered by the size (according to (12)÷(15) DIN 743-2);
- Kσ,τ - is a factor of the surface roughness for normal/tangential stresses (according to Figure B.1 DIN 743-1).

Fatigue strength of a mechanical part implies permanent endurance of a provisionally shaped mechanical part, including all influential parameters. In order to determine the fatigue strength of an actual mechanical part, it is necessary to correct the values of the fatigue strength resulted from the testing of polished specimen with the influential factors in accordance with DIN 743.

Of course, the fatigue strength of a mechanical part is influenced by the complex stresses followed by the overlap of normal and tangential stresses. [6].

Surface hardening factor Kv of the shaft depends on the method of surface hardening (hardening, rolling, shot peening, pressing..) on which the safety factor is tested, but primarily, the surface hardening factor depends on the depth of the surface hardening. The surface hardening enables the induced compressive stresses in the surface layers of the parts to increase the fatigue strength of parts. The influence depends on the depth of hardening, hardened layer, so, for the parts of diameter over 25 mm this factor rapidly decreases. The influence is bigger on the the notched parts (fatigue notch), than on the un-notched parts. The surface can be hardened by chemical-thermal treatments, mechanical and heat treatments in order to increase the load capacity of the part, and/or increase of fatigue strength [6].
The value of Kv factor for the previously mentioned hardening methods can be read in the standard DIN 743-2, Table 4. When reading the Kv factor, besides the hardening method, it is necessary to know on which diameter the safety factor S is tested, whether the effective stress concentration factor $\beta_{\sigma,\tau}$ has resulted from an experiment or geometric stress concentration factor $\alpha$.

The values given in the DIN table for the shafts with fatigue notches are applicable only when $\beta_{\sigma,\tau}, \tau > K_v$.

Also, it is known that $K_v = 1$, for the shafts without and with small fatigue notches, for diameter $d > 40$ mm, while for the shafts with fatigue notches applies:
- for $40$ mm $< d < 250$ mm, $K_v = 1.1$;
- for $d > 250$ mm, $K_v = 1$.

2. TEST METHODS FOR THE DEPENDENCE OF SHAFT SAFETY FACTOR S

The Standard DIN 743 defines a unique procedure for the calculation of the shaft load capacity which is possible to develop in Microsoft Office Excel. Such developed calculating procedure enables quick test of the safety factor on the input data the dependence [7].

The sketch of the critical section where the shaft changes diameter is given in the figure 3.

For the study of the said dependence, the input data have been defined as follows:
- Average roughness height $R_z = 16$ $\mu$m;
- Shaft diameters in range: 10 mm to 40 mm;
- $t = 1; 1.5; 2.5; 5; 7$ i $10$;
- $r = 0.3; 0.6; 1; 1.5; 2; 1.3$;
- Shaft materials: E295, E350, C10E, 20MnCr5, C45, 34CrMo4;
- Shaft loads are random samples in range: 1 Nm to 100 Nm.

Theoretically, the values of Kv factor for stress concentration in the areas where the shaft changes diameter can be within the following limits (based on DIN 743-2, Table 4.), [2]:
- For shaft diameter 10 mm to 25 mm, factor value is $K_v = 1.1 \ldots 2.5$;
- For shaft diameter 25 mm to 40 mm, factor value is $K_v = 1.1 \ldots 1.8$;
- For shaft diameter larger than 40 mm, $K_v = 1.1$.

The dependence of the shaft safety factor $S$ on the surface hardening factor $K_v$ can be illustrated in a diagram with the additional change of only one input data, while the other input data have to remain constant. The input data are mostly chosen for the shafts commonly used in practice, although, there are certain values which are only theoretical (e.g. $K_v = 2.5$, according to DIN, this value hasn't been experimentally confirmed).

It should be noticed that the dependence mentioned in this paper is expressed in percentage using the formula (1).

The dependence is based on the comparison of the safety factor value for $K_v = 1.1 \ldots 2.5$, and/or, the surface hardening value, in relation to the values of the safety factor for $K_v = 1$, and/or, without surface hardening.

$$S[\%] = \frac{S_{K_v = 1.1...2.5} - S_{K_v = 1}}{S_{K_v = 1}} \cdot 100\%$$

The mentioned dependence shall be tested only when the shaft safety factor $S$ is higher than the minimal required safety $S_{min}$, $S > S_{min}$. According to the standard DIN 743, $S_{min}$ has to be at least 1.2. ($S_{min} = 1.25$).

In terms of usage of scientific and research methods, the basic methods for analysis, abstraction and synthesis have been used in this paper, so as the general modeling...
method by which the shaft calculation according to DIN 743 has been developed to a realistic model in Office Excel.

3. RESULTS AND DISCUSSION

In respect to the fact that a similar study has been carried out for the shaft critical sections which represent the source of stress concentration, such as the keyway, and duct fuse [2], similar result are expected in reference to the noticing of significant dependence of the shaft safety factor S on the surface hardening factor Kv.

keyway, and duct fuse, is the fact that the dependence was perfectly linear and it was not affected by the change of shaft diameter and shaft material, nor change of load. With the increasing of the Kv for 0,1, the safety factor also increased for 10%.

The diagram of the dependence of the shaft safety factor S on the surface hardening factor Kv, for shaft diameters ranging from 10 mm to 25 mm, is given in the figure 4.

The dependence was tested for the constant input data , as follows:
- Shaft material E295;
- \( t=2.5 \);
- \( r=2 \);
- load \( M_{ba}=12000 \, \text{Nmm}, M_{bm}=0 \, \text{Nmm} \);
- \( Ta=Tm=6000 \, \text{Nmm} \).

The other type of diagram, with the sama data, is shown in the figure 5 for the better visibility and easier reading of the results.

The two diagrams show a significant dependence of the shaft safety factor S on the Kv factor (for some theoretical values, the safety factor S is increased for 115%). The diagrams also show that in the areas of lower Kv values, the dependence is almost linear and independent of the diameter change, which is not the case in the areas of higher values of Kv factor (approximately above 1,5).

The diagram of the dependence of the shaft safety factor S on the values of Kv factor, for the shaft diameters ranging from 25 mm to 40 mm is shown in the figure 6. The other input data are the same as in the previous case.

The previous diagram shows the approximate linear dependence of the shaft safety factor S on the Kv, as well as that the dependence is not affected by the diameter change for the range of the shaft diameter in question. The Figure 7. illustrates the diagram of the dependence of the shaft safety factor S on the Kv factor, for change (increase) of \( t \) from 1 to 10, and shaft diameter 20 mm. Other input data are identical as in the previous cases. It is known that with the increasing difference between the larger and smaller shaft diameter, and/or, with the increasing \( t \), the shaft safety factor S decreases. But, the following diagram shows that the dependence of the safety factor on Kv increases with the increasing \( t \) for the higher values of Kv, in this case, above 1,7.
Roundness radius, and/or, transition radius on the shaft is very important shaft characteristic and its value mostly depends on the mounting dimensions of the parts which are installed on the shaft. The standard values of the radius are previously stated. The figure 8. demonstrates the dependence of the Kv factor on the roundness radius for the shaft diameter 25 mm and \( t = 5 \). Other input data are identical as in the previous cases. Based on all these diagrams, it can be concluded that the geometry of the critical section where the shaft changes diameter affects the dependence of the shaft safety factor \( S \) on the Kv factor in the areas of higher values of this factor only (approximately above 1.5).

It is well-known that the shafts are manufactured from engineering steels, heat treatment steels, and that the steels with better mechanical properties result with having higher safety factors. However, the study carried out within the scope of this paper, in relation to the test of the dependence of the shaft safety factor \( S \) on the Kv factor, including the change of material used for the shaft manufacture, demonstrates that the material properties do not affect the dependence in question. The table 1. shows the average percentage increase of the shaft safety factor \( S \) with the increasing Kv factor for the materials listed in the paragraph 2. and the figure 9. demonstrates the dependence of the Kv factor on materials, for the following input data:

- Shaft diameter \( d = 20 \) mm;
- \( t = 2.5 \);
- \( r = 2 \);
- load identical as in the previous cases

### Table 1. Average increase of the shaft safety factor \( S \) with the increasing Kv factor for various materials

<table>
<thead>
<tr>
<th>Kv</th>
<th>1.1</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
<th>2</th>
<th>2.2</th>
<th>2.4</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>S [%]</td>
<td>9</td>
<td>35</td>
<td>51.5</td>
<td>67</td>
<td>82</td>
<td>96</td>
<td>108.7</td>
<td>115</td>
</tr>
</tbody>
</table>

This study showed that the change of load value mostly affects the dependence of the shaft safety factor \( S \) on the surface hardening factor Kv. The Figure 10. presents a diagram of the dependence of the shaft safety factor \( S \) on the Kv factor for the following input data:

- Shaft diameter \( d = 20 \) mm;
- \( t = 2.5 \);
- \( r = 2 \);
- Shaft material E295
- \( M_{ba} = Ta = Tm = 15000 \) Nmm; \( M_{bm} = 0 \) Nmm;
- \( M_{ba} = Mb_m = 0; Ta = Tm = 6000 \) Nmm;
- \( M_{ba} = 15000 \) Nmm; \( Mb_m = 0; Ta = Tm = 0 \)

From the previous diagram it can be noticed that the shaft safety factor \( S \) can increase to 150 % when the the torsional moment is equal to zero, and/or, when the shaft is loaded with the bending moment only.

Other studies in this area indicate that the dependence will not increase with the increasing bending moment. The other type of diagram, with the same data, is shown in the figure 11 for the better visibility and easier reading of the results.
The results presented in this paper have shown that the shaft safety factor $S$ significantly depends on the surface hardening factor $K_v$, and/or, that the affect which the surface hardening $K_v$ has on the shaft safety factor $S$ is relevant in comparison to the shafts which were not hardened ($K_v=1$). In other words, during the calculation of the shaft load capacity on critical sections, which represent the fatigue notch, it is not possible to omit the $K_v$ factor. The obtained results might be useful to the shaft designers in the process of choosing the material and dimensions of the shaft. The designers might use the results for the calculation of the load capacity as well. Whether to perform the surface hardening or to change the material and diameter of the shaft in order to increase the shaft safety factor are some of dilemmas the designers face with and where the study results might be helpful. The available working conditions have to be taken into consideration from the economical aspect, and/or, what kind of materials the designer has at his disposal and which technological procedures he can use.

The primary reason would be the fact that the price of the shaft depends on the manufacturing process, and/or, the procedure for the machining of the shaft, and less on the choice of the material. Hence, the price of the shaft can be reduced if there are less surfaces which require surface finish, or in case of lower quality of tolerance which does not endanger the operational safety and reliability of the shaft, and/or, if the functional requirements have been met with the minimum price [6].

Similar study of the dependence of the shaft safety factor $S$ on the quality of the machined surface for the critical sections has already been published [10]. Further studies in this field of work, and/or, studies of the affect of the other influential factors, shall be directed towards the study of the affect of the technological and geometrical size factor.

The method for the determination of the $K_v$ factor values, as well as, the method for the shaft surface hardening haven’t been considered in this paper since they were defined in the standard.

4. CONCLUSION

The studies carried out for the dependence of the shaft safety factor $S$ on $K_v$ factor demonstrate that this factor is the only factor which increases the fatigue strength of the mechanical part in relation to the fatigue strength of the tested specimen. It is due to the total design factor $K_p$, which is less than one for certain values of the $K_v$ factor. This is rarely encountered in practice since those values of the $K_v$ factor are theoretical values and according to DIN they have to be experimentally confirmed.

REFERENCES


