The use of optimization in new design of tribometer specimen clamping system

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Abstract. The article deals with the innovation of the clamping part of the tribometer, where the tested specimens are clamped. The new clamping system was designed in the CAD system CATIA V5. The advantages of the new clamping system are compared with the original clamping system of specimens on the tribometer type A30. The new clamping design is evaluated from technical, technological and marginally also from economical point of view. The new clamping design ensures easy handling and exchange of specimens. Easy handling is ensured by the conical collet, which is released by the fixation nut, and subsequently the specimen can be pulled out and replaced with a new one without disassembly the device. The content of the article is also the strength analysis of the conical clamping collet and subsequent optimization. In the strength analysis, the conical collet is pushed into the conical cavity of the tribometer rotor by an outer fixation nut. The result is a numerical simulation of the new designed clamping system which will consist of the rotor, the conical collet, fixation nut and the tested specimen. The von Misses stresses, deformations and reaction forces acting on the collet will be determined by the numerical analysis. Subsequent optimization consisting of defining the target function, boundary conditions and type of optimization will be found. The minimum necessary fixation force which will be obtained from the fixation nut to ensure the transmission of torque to the clamped specimen without slip.

1. Introduction

When developing new devices, the main emphasis is on their reliability, durability, safety and ecology. These properties can be greatly improved by examining the friction and wear of mutually contacting surfaces that move relative to each other. Tribology deals with the study of these phenomena.

Tribological measurements are performed on specialized single-purpose devices, which task is to measure physical quantities arising from the interaction of two bodies moving relative to each other. In most cases, it is the temperature, the coefficient of friction and the pressing force. One of such devices is the Tribometer A30 manufactured by ZVL Dolný Kubín in 1981. This type of the device is currently being improved using CAD/CAE system CATIA V5. This software finds its application e. g. in the design of new machinery and equipment for areas such as engineering, automotive, aerospace, construction, agriculture industries and energetics [1].

Some packages of these computer programs also include structural analysis, thanks to which the designed devices can be easily verified in terms of strength, where even at the very beginning of the design it is possible to test selected structural parts. These parts are usually the most loaded member of machine parts. Structural analysis in commercial software packages is based on the finite element
method. It is a modern numerical method for solving problems of continuum mechanics and is so far the most universal method known. The finite element method also solves physically nonlinear (plasticity) and geometrically nonlinear (large deformation, stability) problems. It usually solves such tasks that cannot be solved by classical methods [2-4].

Simulated annealing (SA) is a random-search technique which exploits an analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure (the annealing process) and the search for a minimum in a more general system; it forms the basis of an optimisation technique for combinatorial and other problems. Simulated annealing was developed in 1983 to deal with highly nonlinear problems. Simulated annealing approaches the global maximisation problem similarly to using a bouncing ball that can bounce over mountains from valley to valley. It begins at a high "temperature" which enables the ball to make very high bounces, which enables it to bounce over any mountain to access any valley, given enough bounces. As the temperature declines the ball cannot bounce so high, and it can also settle to become trapped in relatively small ranges of valleys. A generating distribution generates possible valleys or states to be explored. An acceptance distribution is also defined, which depends on the difference between the function value of the present generated valley to be explored and the last saved lowest valley. The acceptance distribution decides probabilistically whether to stay in a new lower valley or to bounce out of it. All the generating and acceptance distributions depend on the temperature [5].

2. Problem description

2.1. Original clamping system of tribometer

A conical part made directly on the test specimen is pushed into the conical cavity of the tribometer rotor by means of a long screw (Figure 1). The torque from the rotor is transmitted to the test specimen by friction on conical surfaces. The conical surfaces also ensure the coaxiality of the rotor and the specimen. Such a solution requires a conical ending to be made on each tested sample. In order to ensure these properties, it is necessary that the design of these conical surfaces was accurate. For this reason, the production of precision conical surfaces is a demanding technological operation and therefore also expensive. The handling of the specimens in this setup is complicated and lengthy, as it is necessary to disassemble the entire load head and then pull the screw and the specimen out of the rotor to replace the specimen.

Figure 1. Original design with conical test specimen and screw fixation (left) and new design with conical-type of the spring collet (right).
2.2. New clamping system of tribometer
A conical clamping sleeve (collet) is pressed into the conical cavity of the tribotester rotor by means of a nut, into which the test specimen with a cylindrical end is clamped. By pushing the collet into the conical hole, the collet is compressed, thus forming a clamp connection between the cylindrical end of the sample and the inner cylindrical surface of the collet (Figure 1). The production of the samples has thus been significantly simplified, since it is not necessary to create a conical end on the samples, but only a cylindrical one. In this arrangement, the samples are exchanged by loosening the nut (green), thus released the collet (orange), and the sample can also be easily pulled out through the cavity of the loading head (pale brown).

3. Numerical simulation and optimization
The rotor, the collet and the specimen create a compression joint in cooperation with the nut. By pushing the conical collet into the conical cavity of the rotor, the conical collet tends to compress and thus reduce its inner diameter of the cylindrical hole (Figure 2). However, by inserting the cylindrical end of the specimen into the cylindrical hole of the collet a resistance is applied to this compression, which causes reaction forces to arise between participating parts of the assembly [4, 6].

![Figure 2. Considered state of the new clamping system for the numerical simulation.](image)

3.1. CAD model
The conical collet chucks are standardized components and are manufactured in a variety of sizes and clamping ranges. It is therefore possible to clamp cylindrical specimens with different diameters by changing the collet without problems. In this case was chosen collet SN22 which the geometry and main dimensions are shown in Figure 3.

![Figure 3. CAD model of the conical spring collet SN22 with main dimensions.](image)
3.2. Finite element mesh
The maximal size of the element was set to 2 mm and absolute sag to 0.2 mm. The quality of mesh elements was checked and all generated elements were corrected in the whole volume of the part. In Figure 4, generated finite element mesh is shown, which contains of 28604 elements of the type TE10, 10-nodes parabolic tetrahedrons. The overall number of nodes for these mesh settings is 48372.

![Figure 4. Parabolic tetrahedron element TE10 (left) and the finite element mesh generated using elements TE10 (right).](image)

3.3. Material properties
In the simulation models, material properties of the collet were defined according to Table 1.

| Collet material | Young's modulus $E$ [GPa] | Poisson's ratio $\nu$ [-] | Density $\rho$ [kg.m$^{-3}$] |
|-----------------|--------------------------|--------------------------|----------------------------|
| Steel           | 200                      | 0.266                    | 7860                       |

3.4. Boundary conditions and loads
In the simulation, all interactions between each parts (Figure 2) were idealized by adequate boundary conditions [7-9] which can be seen in Figure 5. The outer and internal cylindrical surfaces have defined boundary conditions as surface sliders with no friction considered behaviour between the surfaces in contact. Surface sliders are surface constraint joins, which allow points of a surface to slide along a coinciding rigid surface. At each point of the deformable surface, the program automatically generates a constraint which fixes the translation degree of freedom in the direction normal to the surface at that point. The loading was defined as axial distributed force on surface where the contact is between the fixation nut and the collet.

![Figure 5. Boundary conditions and loads applied on the collet.](image)
3.5. Type of the analysis
In this kind of numerical simulation, static type of the analysis has been chosen because the fixation nut creates constant load on the collet, and this fixation state is permanent during whole time of the tribological testing process.

3.6. Optimization settings
For the testing of specimens on the tribometer, it is necessary to ensure the torque transmission to be reliably transmitted to the tested specimen. The construction of the tribometer is designed for the maximum torque value of \( M_K = 10000 \text{ N.mm} \) (Figure 6) which can be reached during testing. The safety factor \( k = 2 \) is also taken into account. It is clear from the construction of the collet that if we want to transfer such torque at the value of the friction coefficient for steel-steel contact \( f = 0.3 \), it is necessary that the adequate normal force \( F_N \) acting on the tested specimen will be created through a conical collet on its central cylindrical hole surface [5].

\[
F_N = \frac{F_T}{f} k = \frac{M_K}{f} \frac{1000/11}{0.3} \approx 6060 \text{ N}
\]

Since we already know the value of the required normal force \( F_N \), it is possible to define it as the target value of the optimization function. The algorithm type of this optimization was set on simulated annealing. The axial force \( F_x \) which is found by this optimization has been defined as an optimized parameter. Based on the change of this value, the value of the reaction force is calculated, which should be as close as possible to the value \( F_N = 6060 \text{ N} \), which was calculated according to Equation 1.

3.7. Run optimization
Once we have all the necessary settings set, we can start the optimization process and collect the results in this stage of the numerical simulation (Figure 7).

**Figure 6.** Schematic front view on forces and moments acting on the collet.

**Figure 7.** Detailed optimization settings.
4. Obtained results and discussion

The use of material is a good indicator for evaluating the benefits of a new method of clamping specimens. For the original method of the clamping system, the specimen is made of semi-finished product ø 45×110 mm. The weight of the semi-finished product is 1 375 g and the weight of the real part is 289 g. The use of material in this case is therefore only 21 % and the remaining 79 % is a waste (Figure 8).

![Figure 8. Original design of test specimen (left) and new design of test specimen (right).](image)

In the case of a new design of clamping specimens, the specimen is made of the smaller semi-finished product ø 25×110 mm. The weight of the semi-finished product is thus only 424 g and the weight of the real part is 267 g. The use of material in this case is up to 63 % and only 37 % is a waste. Another advantage of the test sample is cheaper production, because grinding cylindrical surfaces is cheaper than grinding conical surfaces.

By optimization of the strength analysis parameters obtained the value of the force required to press the conical collet into the conical rotor hole by means of a nut in order to obtain the value of the normal force required to produce a frictional force capable of reliably transmitting torque from the rotor to the test specimen. Its value is approximately 3 800 N in the given conditions as can be seen from Figure 9. The minus sign before this value resulted from the geometric orientation of the model, where the direction of pushing was directed to negative values. Thus, the minus sign only determines the direction of action in a given coordinate system.

![Figure 9. Results of optimization for 110 iterations.](image)
At the peak value in 67th iteration is only checking value for finding global minimum value not only local minimum value of the finding parameter. In this case has been returned process of the calculation near the old results what signalize that this solution region is the best of all for finding the optimal solution of this problem. Under the action of such a large clamping force (approx. 3800 N), the values of mechanical stresses (Figure 10) and displacements (Figure 11) for collet were calculated.

5. Conclusions
The innovation of the tribotester clamping system has many advantages. The exchange of samples is simple and fast, because the loosening of the nut becomes an automatic loosening of the clamping system due to the pre-stressing of the conical collet. The collet is a standard part that can be replaced with a new one if it is damaged or lost. The semi-finished product from which equivalent types of new cylindrical samples can be produced represents only 30.9% of the volume of the original conical shaped semi-finished product. Also, the use of material to make new cylindrical specimens is 63% compared to the original conical design, which uses only about 21%. Since the waste of material is minimized in a significant scale, it can be determined that not only from an economic point of view, but also from an ecological point of view, such a solution of clamping the specimen is more advantageous.

The value necessary to push the collet into the conical rotor hole must be 3800 N to ensure a smooth and reliable transmission of torque to the shaft of the test specimen. Reliable torque transmission will only be ensured if the value of the coefficient of friction between the clamping sleeve pair is greater than 0.3. Also, the transmitted torque must not acquire a value 20000 N.mm and the diameter of the shaft must not be less than 22 mm. When pressed with a force of 3800 N, stresses are generated on the collet, which reach a maximum value of approximately 40 MPa. From the values of displacements, it is possible to derive a compressive force of 3800 N necessary to push the collet into the conical rotor hole only 0.005 mm.
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