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Optimisation of turbine shaft heating process under steam turbine run-up conditions

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Abstract An important operational task for thermal turbines during run-up and run-down is to keep the stresses in the structural elements at a right level. This applies not only to their instantaneous values, but also to the impact of them on the engine lifetime. The turbine shaft is a particularly important element. The distribution of stresses depends on geometric characteristics of the shaft and its specific locations. This means a groove manufactured for fixing the rotor blades. The extreme stresses in this place occur during the start-up and the shaft heating to normal operating temperature. The process needs optimisation. Optimization tasks are multidisciplinary issues and can be carried out using different methods. In recent years, particular attention in optimisation has been paid to the use of artificial intelligence methods. Among them, a special role is assigned to genetic algorithms. The paper presents a genetic algorithm method to optimise the steam turbine shaft heating process during its start-up phase. The presented optimization task of this algorithm is to carry out the process of the shaft heating as soon as possible at the conditions of not exceeding the stresses at critical locations at any heating phase.

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Keywords: Genetic algorithms; Steam turbines; Admissible stress; Turbine run-up

Nomenclature

t_{init}	–	initial shaft temperature
$t_{heat\,end}$	–	final gas (steam) temperature
Δt_{time}	–	max. temperature raise in one step
$\Delta t_{time\,x}$	–	arbitrary raise of temperature
σ	–	stress

Subscripts

k	–	arbitrary time period
mut	–	mutation
n	–	running time period
$n-1$	–	preceding time period
$n+1$	–	next time period
dec 10	–	decimal number
bin 2	–	binary number

1 Introduction

Thermal stresses in the thick-walled components of the turbine are the main factor limiting the flexible operation of the turbine. The rotor is the most relevant component of the steam turbine looking from the perspective of its flexible operation and from a safety perspective. For this reason, the turbine rotor is usually protected by the turbine thermal limitation system. The purpose of the turbine thermal limitation system is to determine in real time actual and permissible stresses, which allow to determine relative stress of the rotor. On line information regarding relative stress allows to start up the steam turbine in the shortest possible time and in the same time maintain requested design life of the turbine. It might be concluded that the steam turbine lifetime consumption of the steam turbine due to thermal low cyclic fatigue is minimized for given preconditions as turbine initial condition and thermal boundary conditions during the turbine start-up [1, 2]. The course of start-up planning is also relevant for the process of turbine start-up. A proper steam turbine operation during various transient events like aforementioned start-up or shut down significantly impacts its lifetime, which in the most general case is understood as the ability of an element to perform certain functions under specified operating conditions and at a specified time period [3, 4]. The lifetime consumption of steam turbines may result in unacceptably high deformation, micro-break, deterioration of the strength properties of materials or changes in the structure of materials [5]. Generally speaking, the lifetime of the turbine is determined by the loss of consistency of the components' material.

Planning start-up, the safety factors used in the turbine thermal limitation system depend on the quality of the mathematical model of the supervised component. For this reason, the quality of the mathematical model has a significant impact on the flexible operation of the steam turbine. The more accurate the mathematical model of the supervised turbine element is, the less safety margins can be implemented into steam turbine stress supervisory systems.

The paper presents issues related to the use of genetic algorithms (AG) in the planning of optimal steam turbine start-up. Methods of genetic algorithms are used in various fields of human activity. For example authors of [6–10] applied AG in finances, authors of [11–13] applied AG in medicine, authors of [14, 15] applied AG in building construction, authors of [16–18] applied AG in planning operations and authors of [19, 20] applied AG in steam and gas turbine fields. The technique has so far mainly been used in the processes of design optimisation of various technical objects [17–19]. The neural network were used in turbine run-up process, but give only optimisation five minutes forward [21]. Here, authors present the results of tests in a new field of technical applications. AG methods are used to plan the optimal start-up and heating path of the steam turbine shaft. A part of the real turbine shaft has been selected for testing on the basis of [1, 2]. This part is a steam turbine rotor blade groove, which is a critical location for reaction type blading steam turbine rotors. Considered here approach to optimized rotor warming up to its thermal operational condition is based on simultaneous numerical analysis using classic AG system and Abaqus software, which is a finite elements method software used for the rotor groove stress analysis. The goal of optimization is to reach the minimal warming up time without exceeding stress limit, which represents requested design life of the turbine rotor. It is shown in the paper body that the correct results are achieved using the proposed algorithm.

Presented in the paper topic represents one of the main directions for the development of the concept of the steam turbines operation. This is linked to the increasing share of renewables in the energy market, which necessitates the compensation of power fluctuations in the energy net by conventional energy blocks.

2 Object of investigations

Theoretical studies of steam turbine main components lifetime focus on the analysis of degradation processes of construction materials of these components [1], i.e., the heat fatigue and creep. The material behaviour in the low-cycle fatigue area may vary depending on the condition of the material after heat or technological treatment and the load history [3]. Depending on these conditions, the same material may show cyclic stability, weakening or strengthening. Lifetime in the most general case is understood as the ability of an element to perform certain functions under specified operating conditions at a specified time [4, 5].

There are two main damage mechanisms for steam turbines. The first mechanism is the low-cycle heat fatigue. The second mechanism is a creep. Thermal fatigue is the result of transient thermal stresses resulting from the occurrence of non-stationary temperature fields during the turbine's operating cycle. Creep is the result of operating at high temperatures of turbine components that are loaded both mechanically and thermally.

For the analysis of the heating method, a part of the high pressure (HP) turbine shaft was selected, in which [1, 2] critical stress has been found due to the phenomena described above. The location of its occurrence is the bottom of the groove for fixing the blades. This stress has the most significant impact on the lifetime of the rotor. A discrete model of the selected shaft fragment is shown in Fig. 1.

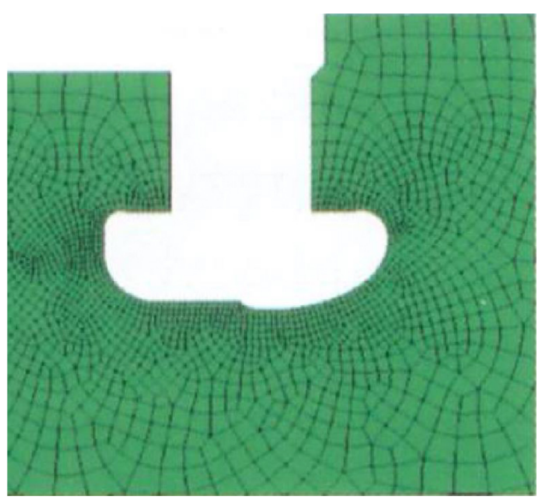


Figure 1: Discrete model of the shaft selected for analysis.

Currently, the only method used in engineering practice to determine the shaft strain of a steam turbine under transient operating conditions is the numerical analysis. A numerical model of the CSD/FEM (computational solid dynamics/finite elements method) of the shaft has been developed to determine transient stress during variable turbine operating conditions.

The turbine shaft is an axial-symmetrical solid, which is sufficient for the purpose of considered in this paper transient events. The assumption of the isotropy of the rotor material also entails the axial-symmetrical nature of the loads of inertia of rotating masses. Axial-symmetrical FEM model was adopted to model the variable operating conditions of the turbine rotor. Modelling by CSD the variable operating conditions of a turbine can be divided into three stages:

1) thermodynamic process modelling in vicinity of considered rotor part,
2) modelling the heat exchange conditions between the steam and the rotor,
3) CSD heat-strength analysis of the rotor.

To make analysis process more robust, the thermodynamic model is separated from the heat transport model in CSD methods.

The permissible stress assumed for the purpose of the analysis is shown in the Fig. 2. The permissible stress represents a stress level which would results in reaching assumed number of required number of load cycles if not exceed during shaft lifetime.

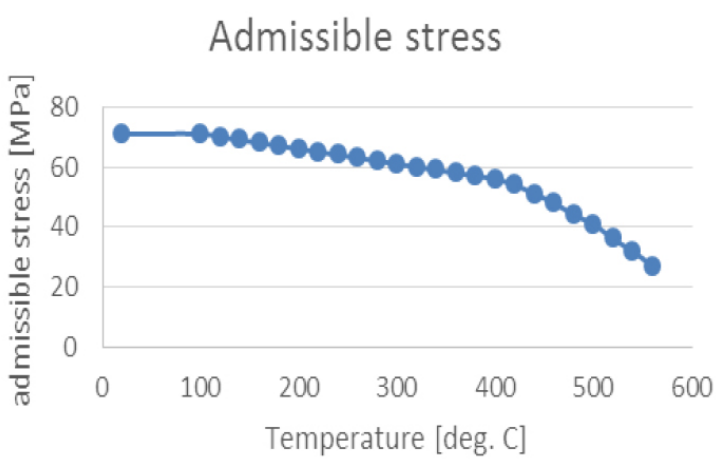


Figure 2: The permissible stress graph σ depending on the shaft temperature.

3 The problem of shaft loads optimisation using genetic algorithms

Genetic algorithms are selected for the research work. In their essence, they are optimizers that use non-standard mathematical methods. This method utilizes to determine the fastest possible steam turbine rotor warming up time together with maintaining required stress level. Particular attention is paid in the paper on one of the operating phases of the proper warming of steam turbines during run-up. Optimization in this case means determining the maximum rate of increase in the turbine shaft temperature while maintaining the stresses generated during the warming of the turbine at critical shaft locations below their limit values. This optimization therefore leads to a maximum reduction in the warming time of the turbine. This is reflected both in minimizing operating costs and in extending the periods of reliable operation of the turbine and the entire power unit. The method of genetic algorithms is used in the presented studies to meet the described strength condition.

In the basic concept, each genetic algorithm (Fig. 3) consists of several items occurring one after each other. The simple algorithm proposed by Holland [22–24] consists of seven stages. It is cited here in order to characterise the structure used for research into the issue of strength under consideration. What is important here is the concept of the chromosome, which in the framework of the presented studies is created by numbers characterizing thermal and instantaneous conditions.

The beginning item is the initiation of the entire algorithm by creating an initial chromosome population.

Next it is followed by an assessment of the adaptation of chromosomes in the population and affects each chromosome in the population.

The third stage concerns the stoppage condition and it depends on how the genetic algorithm is used. There are two stopping conditions. The first occurs when the problem under consideration is about the optimization task. In this case, the condition may be to determine the optimal value (minimum or maximum value). The second case can occur after a specified time of operation of the algorithm or when its operation does not improve the result.

Stage four introduces chromosome selection, which leads to the creation of a new population. Chromosomes with the highest value adaptation function are selected.

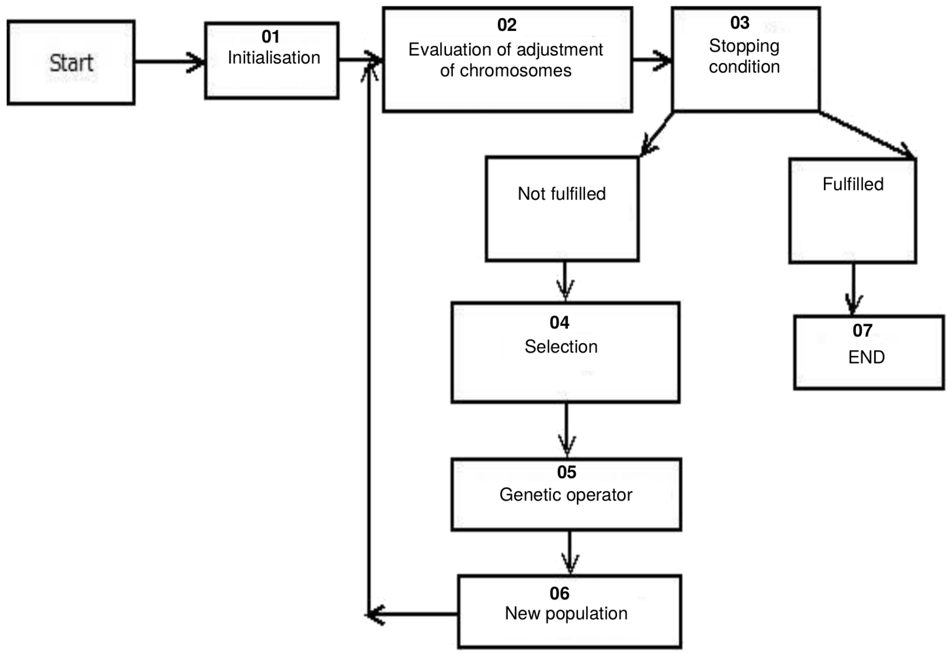


Figure 3: Scheme of a simple genetic algorithm on the basis of [23].

The fifth stage concerns a genetic operator that is used to form a population from chromosomes obtained after the fourth stage. The cross-breeding and mutation operator can be distinguished here.

The penultimate stage concerns the formation of a new population from chromosomes formed after the use of operators from the previous stage. The new population can be subjected to a specific action, that is, to check the condition of stopping the algorithm or to indicate the selected best chromosome.

The last stage is to derive the "best" chromosome and this stage occurs when the stop condition is met. This allows to obtain the result of operation of the entire genetic algorithm. These operations are described theoretically in [22–25]. Presented investigations have been based mainly on conclusions from [26, 27].

The procedure described above has been adapted to cooperation with a numerical CSD program of changing the stresses in the turbine rotor under conditions of a given shaft temperature increase. The optimization procedure selects the highest temperature increase in a given short interval, which does not allow the permissible stresses to be exceeded.

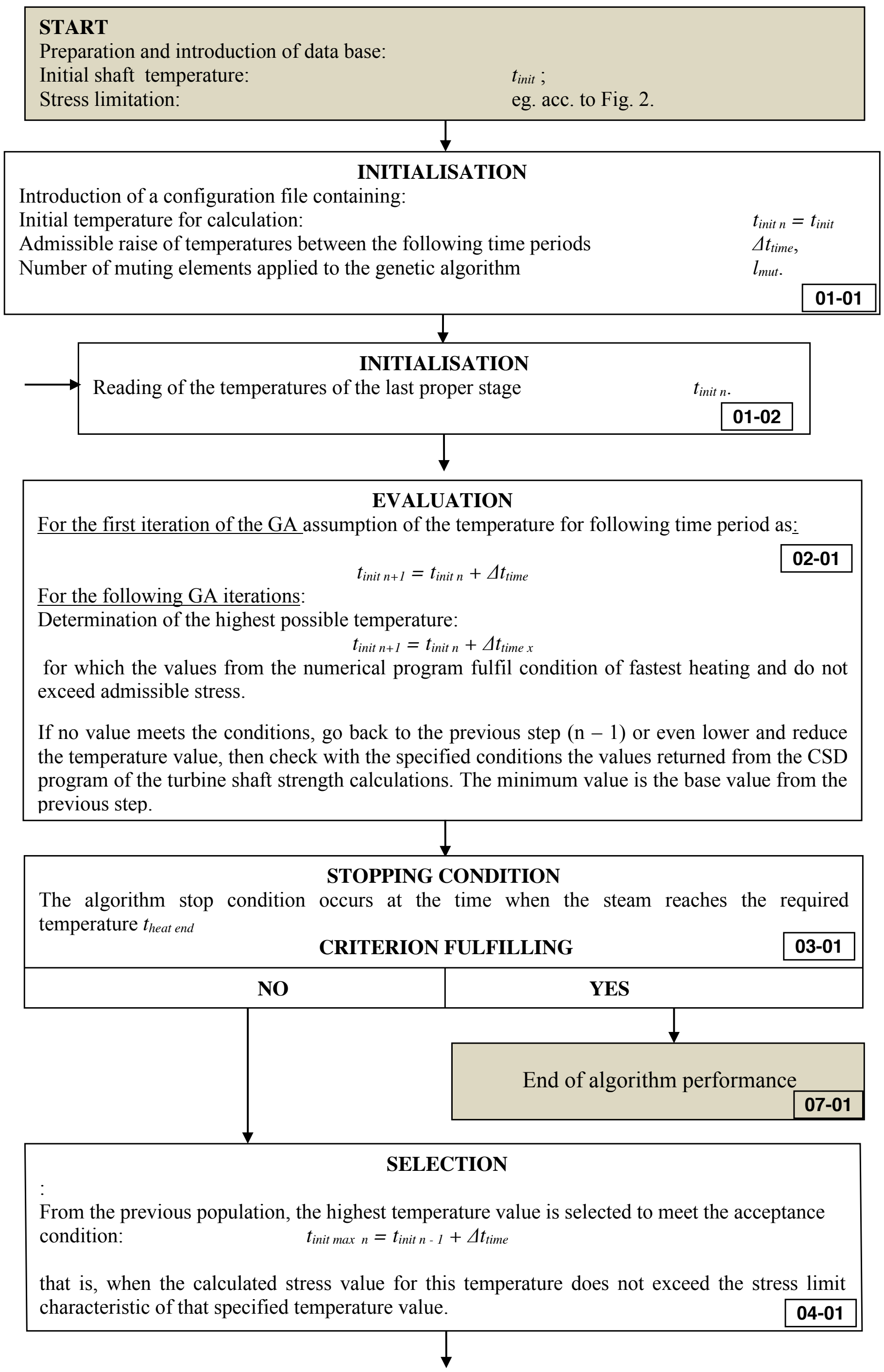
4 Genetic algorithm optimising turbine run-up process

Knowledge of the requirements and optimization criteria set out in the previous chapter allows the genetic method to be adapted to them. The input value for this method is the pre-set temperature depending on the start phase of the turbine associated with the previous operating stage. This means, for example, a relatively low shaft temperature when the turbine is started after a long standstill.

This shaft model or other conditions resulting from operating procedures shall specify other limitations in the warming process of the turbine shaft. In the present case, the condition for not exceeding the permissible stresses is already mentioned in that limitation. The second limitation is the known function of the stress dependency on the value of temperature, Fig. 2. All these barriers shall be taken into account in the development of the genetic algorithm in the selection phases and the retention condition.

The genetic algorithm created below is related to the general scheme of the genetic algorithm presented in Fig. 3. References to the basic genetic pattern of Fig. 2 are made in the different stages of the genetic method cooperating with the numerical shaft strength model. The steps shall be described in two digits: the first one shall refer to the reference of the stage number of the basic scheme (Fig. 2) whereas the second by hyphen to the phase performed within it.

It should be noted that the presented genetic algorithm requires correct cooperation with the numerical CSD stress calculation program. According to the preliminary description, the genetic algorithm in the author's numerical version is designed to select the best pattern of increase in steam (gas) temperature and the rate of heating of moving metal elements. This algorithm prepares inputs (temperatures) for each selected time period for the numerical strength calculation program. This returns the designated stress values as a temperature function to the algorithm. This allows the genetic algorithm to assess the impact and select the parameters of the fastest gas temperature increase, which until the next time period allow the admissible stresses in the moving element to be not exceeded. The algorithm ends when the required metal temperature is finally reached. Important role is played by methods (artificial neural network ANN, or fuzzy logic FL etc.) associated with the genetic and endurance programs of CSD.


START
Preparation and introduction of data base:
Initial shaft temperature: t_{init} ;
Stress limitation: eg. acc. to Fig. 2.
INITIALISATION
Introduction of a configuration file containing:
Initial temperature for calculation: $t_{init\ n} = t_{init}$
Admissible raise of temperatures between the following time periods Δt_{time},
Number of muting elements applied to the genetic algorithm l_{mut}.
01-01
INITIALISATION
Reading of the temperatures of the last proper stage $t_{init\ n}$.
01-02
EVALUATION
For the first iteration of the GA assumption of the temperature for following time period as:
02-01
$t_{init\ n+1} = t_{init\ n} + \Delta t_{time}$
For the following GA iterations:
Determination of the highest possible temperature:
$t_{init\ n+1} = t_{init\ n} + \Delta t_{time\ x}$
for which the values from the numerical program fulfil condition of fastest heating and do not exceed admissible stress.
If no value meets the conditions, go back to the previous step (n – 1) or even lower and reduce the temperature value, then check with the specified conditions the values returned from the CSD program of the turbine shaft strength calculations. The minimum value is the base value from the previous step.
STOPPING CONDITION
The algorithm stop condition occurs at the time when the steam reaches the required temperature $t_{heat\ end}$
CRITERION FULFILLING
03-01
NO
YES
End of algorithm performance
07-01
SELECTION
:
From the previous population, the highest temperature value is selected to meet the acceptance condition: $t_{init\ max\ n} = t_{init\ n-1} + \Delta t_{time}$
that is, when the calculated stress value for this temperature does not exceed the stress limit characteristic of that specified temperature value.
04-01

GENETIC OPERATOR

The configuration file contains information about the number of elements subjected to the l_{mut} mutation process, i.e. the number of bits to be mutated is given.

The mutation process is carried out on the binary numbers of the minimum and maximum temperatures obtained from decimal values through the so-called. gene exchange (consecutive l_{mut} "*0*" or "*1*") so as not to exceed the binary value of the minimum and maximum:

$$t_{init\ max\ \ n\ dec\ 10} \longrightarrow t_{init\ max\ \ n\ bin\ 2}$$
$$t_{init\ min\ \ n\ dec\ 10} \longrightarrow t_{init\ min\ \ n\ bin\ 2}$$

There is an additional condition here so that there is no double mutation of the same number-temperature in a binary string. After mutating, this number is converted back to the floating-point decimal point. The number received in the previous step becomes the base value.

$$t_{k\ n\ bin\ 2} \longrightarrow t_{k\ n\ dec\ 10}$$

Additional temperature-numbers are generated, which must be within the limit from the base number to the base number plus the set value from the configuration file.

Condition: The resulting value cannot repeat with the underlying numbers. If borders are crossed or numbers are duplicated, the mutation process is repeated again.

05-01

NEW POPULATION

When the correct number is obtained, it is left in the batch file and is the input in the calculation of the value for the next time step.

06-01

Back to 01-02

5 Example of the performance of genetic algorithm optimising shaft heating

The result of the developed method of genetic algorithm as a numerical program cooperating with a numerical program modelling the strength of the turbine shaft under heating conditions is presented in Fig. 4. The program is designed to determine the heating speed of the rotating shaft until the required shaft heating temperature is reached with simultaneously controlled stresses in critical positions.

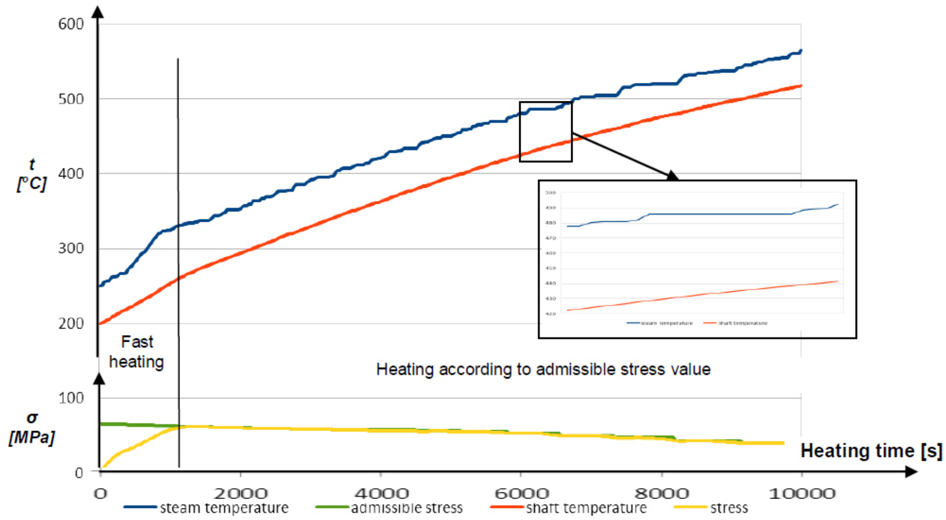


Figure 4: Example of a graph of the increase in the steam temperature and the metal temperature with corresponding increments of the limit stresses as a function of the heating time.

Performance has been done for following assumptions:

Initial shaft temperature: $t_{init} = 200$ °C;

Limits for max. raise of temperature for the time period:

$\Delta t_{time} = 5$ °C/min;

Final temperature of steam(gas): $t_{heat\ end} = 560$ °C.

Shaft stress limit conditions:

- not exceeding admissible stress on the basis of Fig. 2,
- value of the calculated stresses depends on the temperature at which the operation of rotor warming begins,
- calculations are performed for time steps of 1 minute.

The heat of the shaft indicates an even increase in its temperature. The steam temperature increase, on the other hand, is not uniform. There are periods of keeping the temperature constant. The formation of these periods could be seen during the calculation, when it was possible to observe the return of up to several dozen time steps back and the re-determination of the rate of the gas temperature increase. Keeping of shaft's stress below admissible stress at the critical point in the groove is shown in the Fig. 5.

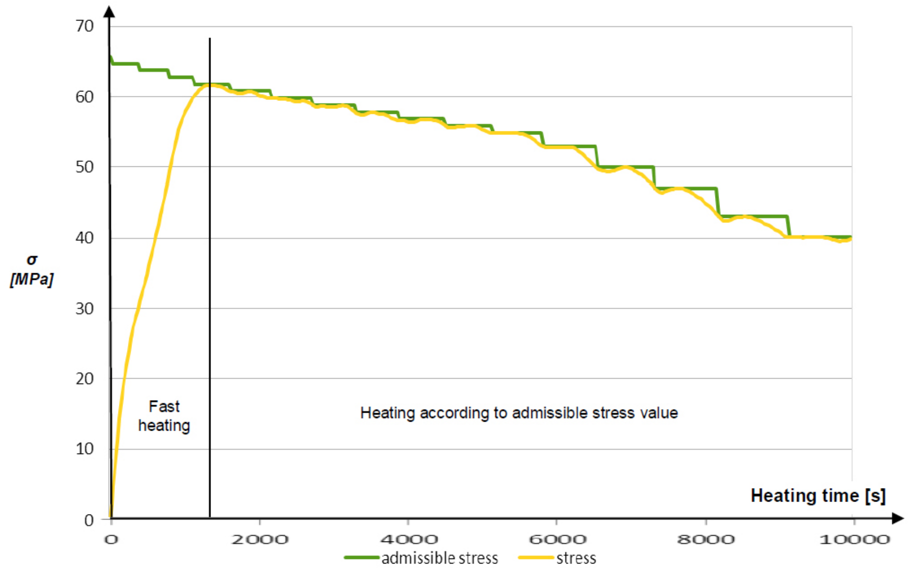


Figure 5: Enlargement of the Fig. 4 showing increments of the limit stresses as a function of the heating time (see Fig. 2) simultaneously fulfilling condition of non-exceeding admissible stress at the critical point in the groove.

6 Summary

In practice, the program's calculation time depends most on the time required by the FEM analysis. The timing of the genetic calculations themselves is very short. This means that genetic calculations are feasible to be implemented into industrial practice where on-line rotors stress models support the analysis in real time. In this case genetic algorithm will not impact the time required for a calculation loop. Time required for optimization is the one which hinders usage of other optimization algorithms in industrial practice. Therefore it can be concluded that genetic algorithms are very interesting possibility to complement the on-line stress supervisory systems with the stress optimization ability.

The numerical procedure of the genetic algorithm requires repeating selection procedures and evaluating the adaptation of the temperature increments, which make it necessary to return from the present calculations to the previous stages of the program and make changes to the minute-increment values of heating temperatures for FEM programs.

Increasing precision in the selection of subsequent temperatures increases the number of steps required to achieve that and depends on the set temperature of shaft heating. This aspect is worth being further investigated before industrial implementation of the genetic algorithms into stress supervisory systems. On one hand, a higher precision will allow for better stress supervisory but on the other hand may lead to elongation of computation time which is relevant for the on-line monitoring systems. Therefore a trade-off should be made in order to have fast stress supervisory algorithm with the best possible accuracy of calculation.

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