

Matrix System for Provision of Performance Characteristics of Gte Heavy-Duty parts at the Design Stage of Technological Processes

T D Kozhina¹, V Yu Eroshkov²

Solovyov Rybinsk State Aviation Technical University

E-mail: proectnir@rgata.ru

Abstract. The paper highlights the methods to assign technological conditions for machining providing the required performance characteristics due to control of quality parameters of a surface layer and machining accuracy. Assignment of technological conditions for machining is performed at the design stage of technological conditions in accordance with the methods developed based on the matrix system of analysis and computation of groups of technological and operational factors.

Introduction

Reliability, operational life and efficiency of gas turbine engines are largely determined by the quality of manufacture of their parts. High accuracy along with low part stiffness, strict requirements to the surface quality and physico-mechanical properties of materials, use of heat-resistant hard-to-cut steels and alloys determines application of progressive methods to obtain work parts and their subsequent machining.

Discs are the most typical GTE parts possessing constructive-technological characteristics according to part complexity. Thus, critical compressor and turbine discs of aircraft engines operate with higher loads under high engine speeds. Necessity to reduce engine weight results in complication of the parts form, forcing to make them hollow. Compressor discs are the most complex to produce in terms of machining, as external faces of these parts feature various combinations of cylindrical surfaces, flanges, gearwheels, blade grooves and other surfaces with low stiffness.

Quality of implementation of GTE compressor disk machining technology is the result of interaction of a wide range of factors to a greater or lesser extent influencing performance characteristics of these parts [1], [2]. Inter alia, even non-mating faces of GTE compressor discs are typically thoroughly machined, various methods of hardening technologies are widely used, as well as those of coating deposition and synthesis and chemical treatment. Discs undergo thermal or thermo-chemical treatment, which complicates technological processes of their manufacture sufficiently, enlarges the cycle of their production due to the necessity to introduce additional procedures and to expand the processing route. To provide the required machining accuracy when designing technological processes in aircraft engine building special attention is paid to the choice of technological bases. With the same purpose surfaces of GTE discs are machined in several steps. When choosing machining methods, especially for finishing operations, possibility of work hardening



and residual stresses has to be taken into consideration⁶ as they noticeably influence performance characteristics of these parts.

Besides, manufacture of aircraft engines excels also through special carefulness of control. All critical parts and components go through the hundred-per-cent control with application of special automated means. However, some hard-to-reach places of such parts can only be controlled by indirect methods at the expense of direct control of the tools and the machining process.

Production engineers have to consider all above-mentioned factors when designing technological processes and computing part cutting modes.

1 Assignment of technological conditions for machining based on computation of groups of technological and operational factors

In practice process engineers need to analyze both the external production factors concerning designer's requirements and product prime cost and the internal ones such as technological infrastructure level and equipment capabilities.

Primarily the technical requirements included in the product drawings are analyzed. Thus, the includes requirements to surface roughness R_a , limit endurance σ_v , quality of seating face machining (polishing), methods of work-piece material control etc. These requirements are fundamental when assigning technological conditions of machining.

Furthermore, the technological conditions of machining have to be assigned which not only would provide specified performance characteristics, but also technical-and-economic indexes or the maximal dimensional tool durability, or the required machining accuracy, and when it is determined by the technological process developed then also the given quality parameters of the surface layer or any other variant of the above-mentioned ones.

Taking systematically into consideration all stages of influence of external and internal factors on the surface layer of the part manufactured affecting the machining process allows forecasting technological heredity of machining heredity and manufacturing end products with required performance characteristics without application of destructive testing methods and finishing processes.

As the recommendation based on the conducted computations the process engineer can offer additional technical requirements providing performance characteristics, which can be introduced by the designer into the drawing.

The obtained results allow to introduce corrections into the existing technological processes changing the structure and the content of the machining itself of heavy-duty parts of gas turbine engines.

Let us consider implementation of these propositions in practice.

As a result of series of studies, the method to assign machining modes was developed based on the matrix analysis of the group of technological factors and performance indexes, as well as the multi-level algorithm based on the matrix to optimize technological conditions of machining providing the required performance characteristics. These tools can be applied for various tasks of process engineers and requirements of designers, which they impose during development part construction and technological process of its manufacture depending on the external and internal environmental factors, i.e. on assignment, operating conditions and technological infrastructure [3], [4].

There is not always the necessity to carry out full-scale computations in practice, i.e. to provide performance indexes of parts through surface layer quality parameters control and to fulfill the technical and economical criteria: maximum efficiency, minimal prime cost or both together. In order to simplify computations the matrix was developed for possible variants of computations based on the optimization multilevel algorithm allowing choosing the required machining mode computations in terms of requirements of a developer or a customer.

Examples of the matrixes for possible variants of computations of technological conditions of machining are presented in Tables in Figure 1. In this case, the following conventional signs are used:

C_{min} are the technological conditions of machining, providing minimal prime cost of the process procedure;

P_{max} are the technological conditions of machining, providing maximal efficiency;

C, P are the technological conditions of machining, providing the optimal combination of prime cost and efficiency in the course of the process procedure;

σ_{-l}, y, I, V are the technological conditions of machining, providing the required limit endurance, convergence value of contacting faces, wear intensity, interface gap volume, respectively, i.e. the performance indexes;

T_p are the technological conditions of machining, providing the specified tool life;

Δ_{wear} are the technological conditions of machining, providing the required tool wear (especially important at tool change);

T_p, Δ_{wear} are the technological conditions of machining, providing simultaneously the specified tool life and the specified wear flat.

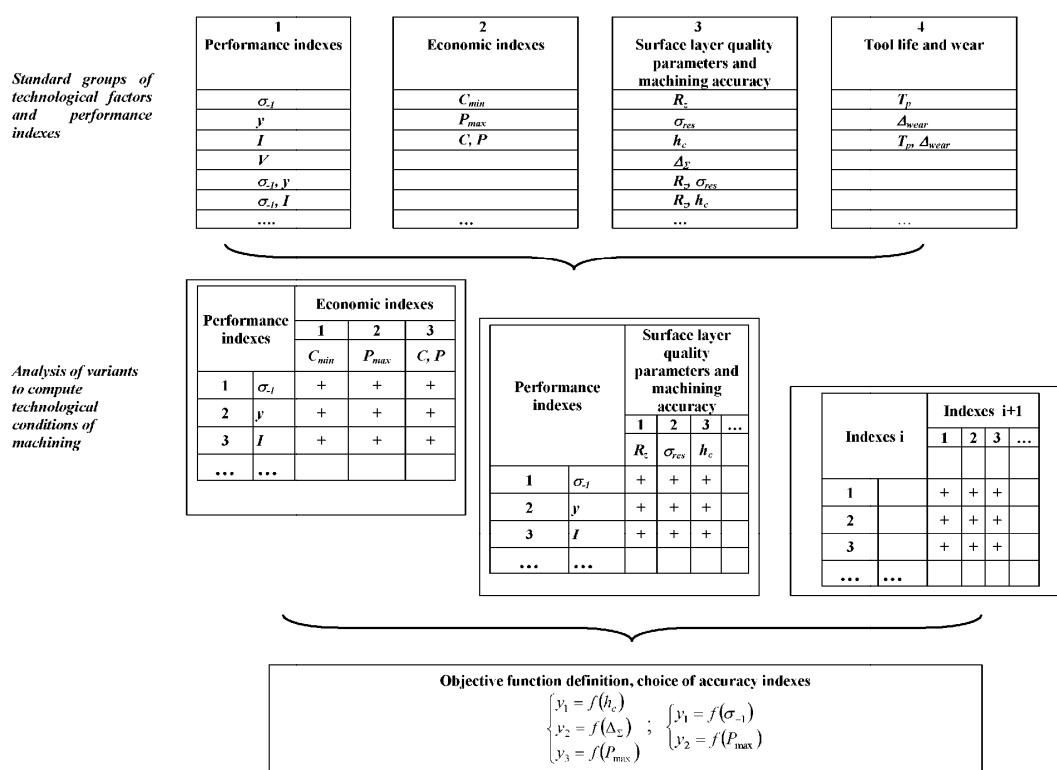


Figure 1. Matrix of groups of technological factors and performance characteristics.

In the rows and columns of the matrix tables (see Figure 2) the possible combinations of various indexes and parameters are presented, which can be needed while machining. At the intersection of rows and columns of the tables by means of conventional signs reasonability of provision of this or that combination of indexes is shown. The sign «+» marks those index combinations which provision is reasonable and can be fulfilled using the optimization multilevel algorithm. Absence of this sign gives evidence that this index combination is not reasonable to be provided because there are direct dependences between some of them.

For instance, development of technological conditions of machining providing the required value of residual stresses and work hardening depth in combination with fulfillment of condition as to the minimal prime cost of machining is reasonable and can be fulfilled by means of the above said algorithm.

On the base of the matrix analysis the conclusion can be drawn, that it is inexpedient to develop the machining modes providing the required values of residual stresses and tool life along with the given values of limit endurance, convergence of contacting faces, wear intensity and interface gap, as the value of residual stresses accordingly to the developed algorithm and the computation method, as well as the tool life depend on the initially specified performance index, and their value is the result of the intermediate in the general computation change, i.e.

$$\sigma_{-1} \Rightarrow f(\sigma_{res}, \Delta_{\Sigma}) \Rightarrow f(S, V, t) \quad (1)$$

If we analyze Figure 1, we can detect the following combinations of indexes and parameters for which provision development of technological conditions of machining applying the optimization multilevel algorithm is reasonable and can be fulfilled:

1. Limit endurance (σ_L), minimal prime cost of machining (C_{min});
2. Limit endurance (σ_L), maximal efficiency of machining (P_{max});
3. Limit endurance (σ_L), optimal combination between the prime cost and the efficiency of machining (C, P);
4. Value of convergence of contacting faces (y), wear intensity (I), value of aggregate error of machining (Δ_{Σ}), minimal prime cost of machining (C_{min});
5. Limit endurance (σ_L), value of convergence of contacting faces (y), interface gap volume (V), value of aggregate error of machining (Δ_{Σ}), maximal efficiency of machining (P_{max});
6. Limit endurance (σ_L), value of convergence of contacting faces (y), interface gap volume (V), value of aggregate error of machining (Δ_{Σ}), optimal combination between the prime cost and the efficiency of machining (C, P);
7. Limit endurance (σ_L), wear intensity (I), interface gap volume (V), value of aggregate error of machining (Δ_{Σ}), minimal prime cost of machining (C_{min});
8. Surface roughness (R_z), value of residual stresses (σ_{res}), tool life (T_p);
9. Value of convergence of contacting faces (y), interface gap volume (V), value of residual stresses (σ_{res}), value of aggregate error of machining (Δ_{Σ}), tool wear flat (Δ_{wear}), optimal combination between the prime cost and the efficiency of machining (C, P) etc.

For example, it is necessary to define the technological conditions of machining providing the specified value of aggregate error of machining and depth of work hardening in terms of maximal efficiency or the specified limit endurance and maximal machining efficiency. This is done as follows:

- 1) before starting the command to the control program is given to choose the objective function, in this case:

$$\begin{cases} y_1 = f(h_c) \\ y_2 = f(\Delta_{\Sigma}) \\ y_3 = f(P_{max}) \end{cases} \quad \text{or} \quad \begin{cases} y_1 = f(\sigma_{-1}) \\ y_2 = f(P_{max}) \end{cases} \quad (2)$$

- 2) the computation is conducted in accordance with the method presented above, where the result is assignment of feed, speed and cutting depth (taking into account machining allowance), and, if it is necessary, recommendations are given as to change the initial tool geometry ($\varphi, \varphi_l, r, \alpha, \gamma, \dots$),

- 3) computation of technological conditions can be carried out both in the batch and the dialogue modes in dependence with customer's requirements.

Taking systematically into consideration all stages of influence of external and internal factors on the surface layer of the part manufactured affecting the machining process allows forecasting technological heredity of machining heredity and manufacturing end products with required performance characteristics without application of destructive testing methods and finishing processes. The obtained results allow to introduce corrections into the existing technological processes changing the structure and the content of the machining itself of heavy-duty parts of gas turbine engines.

2 Industrial implementation of the method to define technological conditions of machining and results of experimental research of parts and samples

Let us consider the technological process of GTE compressor disc manufacture as an example of practical application of research results under conditions of industrial enterprises, as well as structure of its change in the context of application of automated system to control technological conditions of machining (Figure 2, Table 1).

Computations show that for various turning operations (to turn faces 1, 4, 5,..., 12, 13, 14, ...) practically one and the same cutting mode is assigned ($S=0.2\text{mm/rev}$, $n=48\text{rpm}$), independently from various cutting length and allowance value Δ . If we use the reference data at that, as can be seen from the table, it does not practically change anything in the process of the turning operation, moreover even in comparison with the factory technology the reference material reveals excessively overrated cutting speeds without taking into consideration the roughness height value of the surface machined specified in the drawing.

This is confirmed by factory testing of the compressor disc of one of commercially available GTE products machined in accordance with the existing technology: phosphor glow was detected in the form of longitudinal cracks on the disc body (Figure 3, a).

Table 1 Fragment of technological process of turning operations of 2 stage GTE compressor disc (disc material: VT3-1)

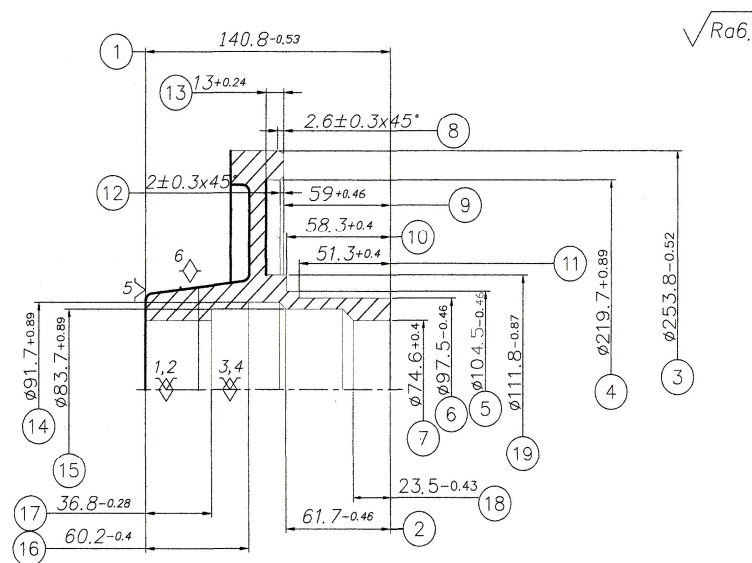


Figure 2. Outline of GTE compressor disc work-piece machining in turning operation.

I Existing industrial technology	II Reference data
Tool material – VC8 $\varphi = 45^\circ$, $\varphi_l = 15^\circ$, $\alpha = 5^\circ$ $\gamma = 5^\circ$ } grinds the worker $r = 0.5 \text{ mm}$, $l_{mach} = 50 \text{ mm}$, $t = 1.5 \text{ mm}$, $S = 0.2 \text{ mm/rev}$. Quality parameters: $R_a = 2.5 \mu\text{m}$, $\Delta = \begin{smallmatrix} 0.00 \\ -0.26 \end{smallmatrix} \text{ mm}$.	Tool material – VC8 $\varphi = 45^\circ$, $\varphi_l = 15^\circ$, $\alpha = 5^\circ$, $\gamma = 5^\circ$, $r = 0.5 \text{ mm}$, $l_{mach} = 50 \text{ mm}$, $t = 1.5 \text{ mm}$, $S = 0.2 \text{ mm/rev}$. Surface machining ←: $V = \frac{125}{T^{0.35} \cdot 0.2^{0.4} \cdot 1.5^{0.2}} = \frac{125}{T^{0.35} \cdot 0.525 \cdot 1.08} = \frac{220.5}{T^{0.35}}$

	n	S	i	Cutting mode: at $T = 60$ min, $V = 52.6$ m/min = 0.876 m/sec, $n = 200$ rpm, $S = 0.2$ mm/rev.
1) To turn face 1	48	0.2	2	
2) To turn faces 4.5 and R 3.6	48	0.2	2	
3) To turn face 11	48	0.2	2	
4) To turn faces 12, 13, 14 and R 18	48	0.2	2	
5) To turn flat face 10	48	manu al		

It must be noted that the crack start its formation from the surface and spreads to the depth, i.e. fatigue comes from the surface. At that compressive residual stresses develop which values varies from -200 to -480 MPa at depth of the work hardening layer more than $40\text{ }\mu\text{m}$, with degree of work hardening 13-29% and loss of material ductility.

Inspection of mechanical properties carried out on the samples manufactured from the rim and the hub parts gives evidence that after the long-term operation material microstructure on the product (operating time: 4805 cycles) is satisfactory, and the cracks are located on the grain node, which is typical for fatigue (Figure 3, b). The total length of fatigue cracks is 6-10 mm, their depth is up to 0,7 mm.

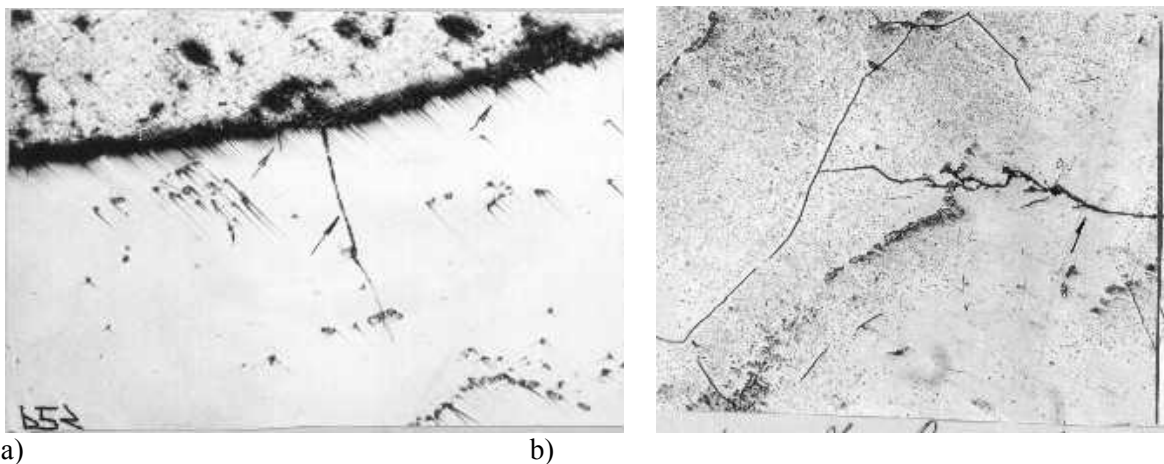


Figure 3. View of crack formation in the compressor disc body:

a) photograph of disc microstructure (magnification $\times 200$),

b) view of the crack in the disc micro section (magnification $\times 200$).

Fatigue fractures formed in the discs in the process of testing because the factory mode, presented in Table 6, corresponds to work hardening depth $86\text{ }\mu\text{m}$, if it is computed according to the method suggested here, and it is proportionately with depth of crack spreading (0.4-0.7 mm). Results of factory testing give evidence that none finishing method will remove the fatigue fracture spreading in depth of 0.7 mm, but will only harden the surface of the part machined, not solving the durability problem at that.

If we make use of the developed computation program for technological conditions of machining (Table 2), not changing the structure of technological process, we can obtain the cutting mode corresponding to the standard value as to the value of cutting speed, and as to the value of roughness height of the surface machined with the considerably lesser one ($R_z = 9.8\text{ }\mu\text{m}$) in comparison with the one specified in the drawing, with value of work hardening layer $h_c = 86\text{ }\mu\text{m}$ and cutting inaccuracy $\delta_z = -67.75\text{ }\mu\text{m}$ [5], [6].

Table 2 Computation according to the developed method and program (tool material VC8 ($\varphi = 45^\circ$, $\varphi_l = 15^\circ$, $\alpha = 5^\circ$, $\gamma = 5^\circ$, $r = 1\text{mm}$, $\rho = 30\text{ }\mu\text{m}$, $\delta_{\text{wear}} = 100$)

№ of face	R_{out}	t_{cut}	l	Required characteristics		Design characteristics				Quality parameters			
				R_z	δ_{diam}	S	V	n	t	R_z	δ	h_c	σ_{res}
6	157	2	49, 6	10	-20...0	0.247	0.326	39.7	2.77	10	-19.61	180	-270
				10	-10...0	0.247	0.323	39.2	1.78	10	-10	160	-360

Therefore, when machining in accordance with the factory technology the reserves of the process itself are not taken into consideration; and when assigning the cutting mode according to the reference data cutting accuracy is completely excluded.

Testing results of the compressor disc machined in the new modes and inspection of micro-sections showed absence of apparent defects (there are no fatigue fractures spreading in the considerable length) (Figure 4), i.e. they confirmed adequacy of the method developed and accuracy of computations.

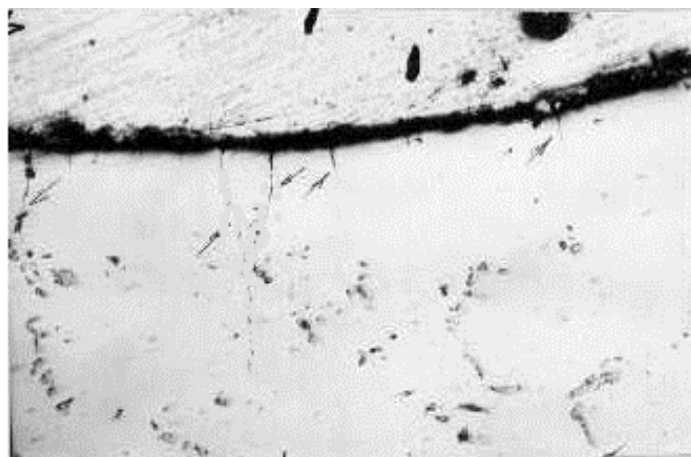


Figure 4. Disc microstructure after LUM-control (magnification×200)

Conclusion

Having regard to the above, it can be concluded that in the existing technology of machining of a standard GTE compressor disc the cutting modes are assigned inconsistently and certain elements of output parameters of machining are considered only indirectly, not to speak of the tool geometry selection procedure. Both the external factors connected with disc operation and the internal ones connected with its machining are not considered. In accordance to the analysis of technological processes and analysis of disc factory tests it should be considered that the modes necessary to machine critical GTE parts, in particular discs have to be assigned strictly controlled subject to the groups of technological and operational factors in order to avoid the defects described above.

In order to solve the above problem the developed mathematical tools can be employed allowing assigning technological conditions of machining. To increase efficiency and reliability of computations a multi-level optimization algorithm was applied which allows carrying out optimization search with usage of additional technological conditions of machining chosen by the process engineer, which increases sufficiently capabilities of the system developed. The distinctive feature of the methods created is the possibility of its application for various output data, various machining methods, various technological procedures and application in various automatic control systems due to the possibility of flexible change of computation algorithm elements.

Analysis of production technologies [5] - [8] implies that the approach suggested to assignment of technological conditions of machining makes possible to create technologies allowing to sufficiently

reduce time for introduction of new products and to increase their service reliability and durability due to change in the existing approach to normalization of technological procedures: reduction of pass sequence in the operation; withdrawal of expensive finishing operations; forecasting of part performance properties.

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