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Approaches for Mechanical and Technological Designing of Welded Items Used in Large-Capacity Power Installations

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Abstract—Stages through which welded items of power installations are designed in mechanical and technological respects are analyzed. Results obtained from theoretical and experimental studies of the criteria for local brittle fractures used during manufacture and operation of welded structures are given. The most efficient methodological approach for designing constructions and technologies is substantiated.

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The main line in which modern power engineering is developed involves construction of economically efficient and reliable power installations, which is achieved through increasing their capacity and optimizing their operating parameters (temperature and pressure of working medium). Use of new high-strength materials for this purpose entails the need to achieve essentially better quality of technological and design elaborations. Under the conditions of strong competition, decreasing the net cost, and shortening the time taken to develop and manufacture the equipment are becoming the main objectives. One of lines in which the above-mentioned objectives can be achieved consists of applying welded items that make it possible to use combined constructions consisting of materials containing different alloys, as well as of billets fabricated as a result of various secondary conversion processes (rolling, casting, and forging).

Contradictions between the designers, specialists in materials science, process engineers, and production structures always arise in the course of developing new equipment. Lack of interaction between them usually results in that equipment is designed with poorer quality, that the materials are selected inadequately, that nonoptimal technological processes of equipment manufacture are developed, due to which there is high probability that flaws (cracks and discontinuities) and zones with pronounced structural and mechanical nonuniformity may appear during manufacture and operation, and as a consequence, that the actual performance characteristics of new equipment will differ from the design ones. Work on finalizing the design and technology at the stages of manufacture and operation result in a considerably longer time taken to develop a power installation and, accordingly, in a higher net cost of this installation.

Welding is one of the main technological processes determining the operability of a construction. Use of welding essentially alters the stressed state of a construction and mechanical properties of local zones in welded connections. In addition, it results in a higher risk of the occurrence of technological cracks and plastic deformations causing distortion of the design geometry of parts and assemblies. Application of the optimal welding technology makes it possible to achieve high quality and reliability of the construction. At the same time, it should be noted that even a slight change in the design of welded items and correct choice of materials can make it possible to use an essentially simpler technology and apply the most suitable welding methods. Therefore, welding technology must be developed jointly with working out the design and selecting the material.

The general principles of combined mechanical and technological designing were formulated by a number of outstanding scientists, including N.O. Okerblom, G.L. Petrov, G.A. Nikolaev, V.N. Zemzin, V.A. Vinokurov, N.N. Prokhorov, G.P. Karzov, F.A. Khromchenko, and some others. The cycle of combined mechanical and technological designing is implemented in carrying out interconnected stages through which equipment is developed. Feedforward and feedback links are formed between the development of construction, selection of materials, elaboration of technology, and the stage of equipment manufacture (Fig. 1). Below, interactions between the individual stages of developing a construction are considered in more detail.

Development of a construction (designing). The initial stage of designing includes development of a draft design with separation of individual items, preliminary selection of the design makeup of the main items and parts (all-forged, cast, welded, welded-and-forged, and welded-and-cast), determination of the temperature and force parameters of operational loads, and definition of strength requirements for materials and welded connections. At the first stage of designing, preliminary selection of materials can efficiently be made using various nomographic charts demarcating the application fields of materials depending on their

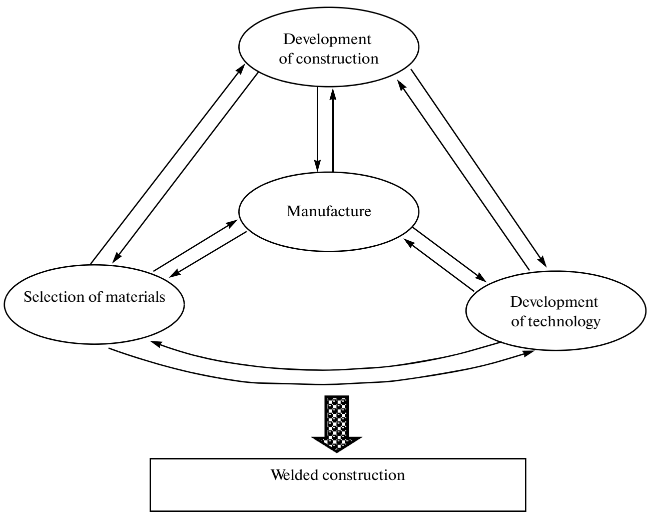


Fig. 1. Interconnection between the stages of combined mechanical and technological designing and manufacturing of welded constructions.

strength properties, safety margin, and stress concentration factors in the most heavily stressed zones of the construction. An example of one nomographic chart is given in [1].

At the second stage of designing, design engineers, working jointly with process engineers and specialists in materials science, work out additional requirements for materials of the main items in order to fulfill the strength characteristics specified by the designer (safety margins and strength degradation factors of welded connections), the required design service life, high resistance to brittle fracture, and technological strength against fracturing (weldability). Concurrently with this, the designer carries out the necessary strength calculations and elaborates in more detain the design makeup of items with direct participation of the process engineer.

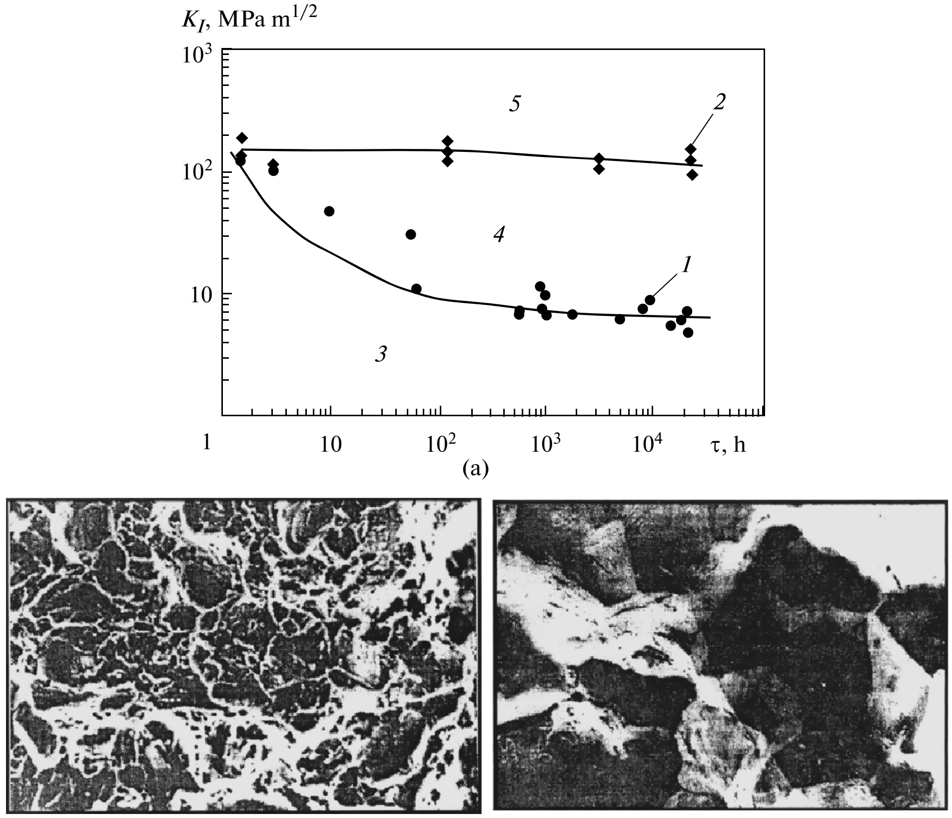
In analyzing the overall strength and geometrical stability of welded items, the designer can limit himself or herself to consideration of equivalent working stresses and averaged temperatures related to the entire volume of the metal of a structural element. However, in estimating the integrity of a structure, local stressed state must first of all be studied. The majority of defects in and destructions of welded items are local in nature and are connected exactly with development of structural, mechanical, and chemical nonuniformities in the zones of welded connections. Taking into account the results obtained from a study of structural and mechanical nonuniformity of welded connections, the designer can make calculations of stressed and strain state essentially more confident and change the design jointly with the process engineer by placing welded joints away from the zone of increased stresses. Despite the fact that various software systems are presently available using which it is possible to simulate operational effects on structural elements and determine the distribution of temperatures, deformations, and stresses taking into account the geometry of items specified by the designer, a calculated analysis of the hazard of local brittle fractures still involves certain difficulties. A paradoxical situation occurs, in which local stressed and strain state can be determined with high trustworthiness by means of numerical computation methods, whereas attempts to estimate the conditions under which brittle fracture occurs in welded items at the stage of mechanical and technological designing are not met with success due to lack of quantitative engineering criteria for local brittle fracture. Criteria for local fracture must be sufficiently universal and simple for the possibility of carrying out the analysis and considering different versions of a construction within the time scheduled for elaborating the design.

For carrying out a quantitative analysis of resistance to local fractures under creep conditions at high temperatures, specialists of the Central Boiler–Turbine Institute (TsKTI) have developed a phenomenological model of brittle fracture [2–15] and criteria using which fast quantitative calculation assessments can be carried out at the stage of mechanical and technological designing. The model describes the kinetics characterizing the accumulation with time of local defects in individual zones of a construction and global defects outside of stress concentration zones. The following engineering criteria have been proposed on the basis of the theoretical fracture model and experimental studies: critical K_c and threshold K_{Icth} [the letters in the subscript have the following meaning: *I* denotes the type of loading (*I* means breaking off), *c* is creep loading, and *th* denotes the threshold value)] time characteristics of fracture resistance, isochronous dependences of crack growth rates in time on the stress intensity factor, using which one can predict all development stages of local fractures: conditions under which cracks do not propagate, kinetics of slow crack growth under creep conditions, and critical conditions for spontaneous fracture in any zone of welded con-

Table 1. Results from determination of the critical and threshold fracture toughness values for different structural classes of steels under creep conditions

Steel grade	K_{Icth}, MPa m$^{0.5}$	K_c, MPa m$^{0.5}$	T_t, °C	τ_t, h
12Kh1MF	6–9	100–132	550	2.2×10^4
15Kh1M1F	17–23	125–140	550	1.3×10^4
25Kh1M1FA	15–20	108–122	550	1.2×10^4
15Kh11MF	53–59	118–136	550	9×10^3
08Kh18N9	26–29	143–152	550	1.3×10^4
08Kh18N10T	17–19	130–148	550	1.2×10^4

Note: T_t is the temperature of tests, and τ_t is the time of tests.



(b) (c)

Fig. 2. Time dependences of K_{Icth} and K_c for Grade 12Kh1MF steel ($\sigma_{0.2}^{20}$ = 390 – 430 MPa) at $T_t = 550°C$. (a): (*1*) K_{Icth}, (*2*) K_c, (*3*) region in which no fracture occurs, (*4*) region corresponding to slow growth of cracks, and (*5*) region in which spontaneous fracture occurs; (b) intergranular fracture in zone *5* (×500 magnification); and (c) intergranular fracture in zone *4* (×500 magnification).

nection taking into account the quality of main metal and the technological heredity acquired in the course of manufacture.

As an example, Fig. 2 shows time dependences of threshold and critical values of fracture toughness corresponding to the local and global damageability of Grade 12Kh1MF steel under creep conditions. The figure also shows fracture graphs (fracture surfaces), the dependence of fracture micromechanisms on the fracture localization degree [15]. Table 1 gives the threshold and critical values of fracture strength characteristics for different grades of steel tested under creep conditions. The threshold values of K_{Icth} are a factor of 15–20 smaller than the critical values of K_c, and their values for welded connections of the above-mentioned grades of steel are still smaller. Table 2 gives the values of K_{Icth} for metal of the near-weld zone (NWZ), weld joint metal (WJM), and the base metal (BM). The local fracture strength characteristics of different zones differ considerably from each other depending on the degree of alloying the material and welding method. The threshold characteristics of fracture strength are used for estimating the service life of different elements of power equipment and welded connections. At the first stage of calculation, the condition under which a crack does not propagate is determined:

$$n_k = K_{Icth}/K_I > [n], \qquad (1)$$

where n_k is the fracture strength margin factor, and $[n]$ is the permissible safety margin [10].

Table 2. Results from determination of K_{Icth} for welded connections in the local zones of main metal (MM), near-weld area (NWA), and weld metal (WM)

Steel grade	$K_{I\tilde{n}th}$, MPa m$^{0.5}$			T_t, °C	τ_t, h
	MM	NWA	WM		
12Kh1MF	6–9	4–5	12–15	550	2.2×10^4
15Kh1M1F	17–23	9–12	12–15	550	1.3×10^4
25Kh1M1FA	15–20	8–13	14–17	550	1.2×10^4
15Kh11MF	53–59	31–40	60–68	550	9×10^3
08Kh18N9	26–29	20–23	23–25	550	1.3×10^4
08Kh18N10T	17–19	8–9	23–25	550	1.2×10^4

If $n_k \leq [n]$, the remaining design service life is determined from the crack growth kinetics based the following condition:

$$a(\tau) \leq [a], \quad (2)$$

where $a(\tau) = \int_0^{\tau} \dot{a}(\tau) d\tau_e$; $[a]$ is the permissible size of a crack, and $\dot{a}(\tau)$ is the isochronous crack growth rate [15].

The permissible values of $[n]$ and $[a]$ in expressions (1) and (2) are specified by the designer together with the process engineer.

Selection of structural materials. At this stage of combined mechanical and process designing, the specialist in materials science selects a steel grade or alloy proceeding from the parameters of working medium, levels of temperatures and stresses, and loading pattern (static, dynamic, or cyclic) specified by the designer. Correct choice of materials made taking into account their thermal and physical characteristics (heat conductivity and linear expansion coefficients, and heat capacity) is of special importance, because these characteristics are used in design calculations for determining thermally stressed state. In selecting the materials, it is necessary to ensure the required level of strength and plastic characteristics and stability of the properties of materials throughout the entire design service life. In selecting the materials, proper attention should be paid to uniformity of properties over the cross section of billets and susceptibility of materials to localization of fractures due to the presence of metallurgical flaws (various sorts of discontinuities, foreign inclusions, and liquation zones).

The proposed structural materials must be estimated with respect to their suitability for welding. The requirements for selected materials may be essentially changed according to recommendations of process engineers. In the cases when new materials have to be used, the properties of metal must be investigated according to programs developed jointly by the designer, specialist in materials science, and process engineer. The use of such an approach will make it possible to considerably shorten the time taken to create a new material for concrete kinds of equipment and achieve considerably lower probability of design errors.

Special attention must be paid to welded items made of different grades of steel operating at high temperatures. Diffusion processes develop in the zones of welded connections of different grades of steel characterized by considerable initial heterogeneity of their properties under the conditions of long-term loading at high temperatures, which entail formation of brittle and low-strength interlayers and occurrence of local stressed and strain state that is essentially different from the design state. If the designer knows only the properties of the main and deposited metal, he or she cannot determine the safety factors and design service life. In this case, a set of additional studies on establishing the properties of metal in different zones with determining the local fracture strength characteristics must be carried out.

For the designer be able to estimate the influence of temperature effects on the level of stresses and on the strain state within the framework of selecting the materials, he or she must have the results from studies of creep characteristics and relaxation of stresses for the base metal and for different zones of welded connections.

Information contained in all the above-mentioned characteristics of metal and welded connections must allow the designer to perform trustworthy simulation of the stressed-and strain state of the construction for ensuring its guaranteed service life.

In developing a new power installation with an increased power capacity that must comply with the requirement of having a decreased metal intensity, the designer is compelled to increase the level of stresses in its components and, accordingly, to use high-strength materials. But as the strength of material increases, the indicators characterizing the technological and operational fracture strength of metal decrease considerably and, consequently, there is an increased risk of brittle fracture. The presence of structural stress concentrations, as well as metallurgical and technological (welding) flaws facilitates development of brittle fractures. Figure 3 shows the decrease of the permissible size of defects with increasing the yield strength ($\sigma_{0.2}$) for chromium–molybdenum–vanadium steels. It can be seen that, as the strength level of steels increases by a factor of 1.6–1.7, the permissible size of a defect with respect to the condition of local brittle fracture decreases by a factor of 9–10 [2–6, 11, 12, 15]. A conclusion can be drawn from what was said above that in selecting materials for welded parts it is necessary to consider not only the strength characteristics of metal, but also pay special attention to enhancement of requirements to its metallurgical quality in the part of imposing more stringent norms on the sizes of permissible flaws.

Development of welding and surfacing technologies. At the first stage of the welding process, the process engineer analyses the overall design of a welded item and technical requirements for operating parameters, and also the materials suggested for manufacture from the viewpoint of ensuring weldability. Based on a preliminary analysis, he or she selects welding methods and welding materials taking into account the strength properties of metal specified by the designer and optimizes the design of welded items, versions of grooving for welding, and the layout of weld joints.

At the second stage, a program is developed for determining the optimal parameters of technological welding processes and thermal treatment. This stage is commenced with the following: the welding process is simulated, the temperature field in the welded connection is determined, the kinetics of change in the stressed-and-strain state is evaluated, and the zones in which structural and phase conversions evolve are estimated.

The kinetic dependences are used for experimentally simulating the deformation and destruction of material in different zones of welded connections during tests of samples of the studied metal and for determining its resistance to technological cracks. Development of quantitative engineering criteria for technological resistance to crack growth, as well as metrologically supported test methods, is of the most important significance for implementing such an approach.

The results obtained from long-term studies and theoretical elaborations carried out at TsKTI made it possible to establish general regularities in the development of technological cracks during welding and thermal treatment [16–27]. It was shown that hot and cold cracks appearing during welding and cracks resulting from thermal treatment develop according to the mechanisms of brittle intergranular fracture under the effect of temporary and residual welding stresses. The formation of these stresses is characterized by kinetic regularities of creep and embrittlement in certain temperature and time intervals corresponding to nonequilibrium state of metal in the corresponding zone of welded connection [23, 24]. An analysis of phenomenological regularities in the development of this type of failures makes it possible to describe technological cracks in welded connections using the statements of general creep fracture theory. New criteria for technological resistance to crack growth similar to the fracture criteria under creep and stress relaxation conditions have been developed. For quantitatively assessing the resistance to cold cracks and cracks appearing during thermal treatment, it has been proposed to use threshold fracture strength values determined according to special procedures [28–30] under creep and stress relaxation conditions. The loading parameters are established based on the results of the previous simulation. The resistance to hot cracks is determined from the dip of plasticity in the temperature interval and from the actual deformation rate obtained from a preliminary calculation at the stage of simulating the technological process of welding [27].

The temperature and stressed-and-strained states are simulated by means of the developed computer program using the finite-element method. The mechanical model (the geometric relations and schemes characterizing the state of deformed medium) has been implemented according to the classic theory of strains and stresses. In the physical model characterizing the form of correlation between stresses and strains, and which is based on the statements of theory of nonisothermal plastic yield, the limiting condition is adopted in Mises form, and the hypothesis of short-term creep is used. The temperature problem is based on the unsteady equation of heat conductance with initial and boundary conditions. The loading history was traced by sequentially solving the temperature and strain problems in nonlinear statement at each moment of time taking into account the dependence of thermophysical and mechanical properties of materials on the temperature and the thermokinetic diagrams of phase conversions.

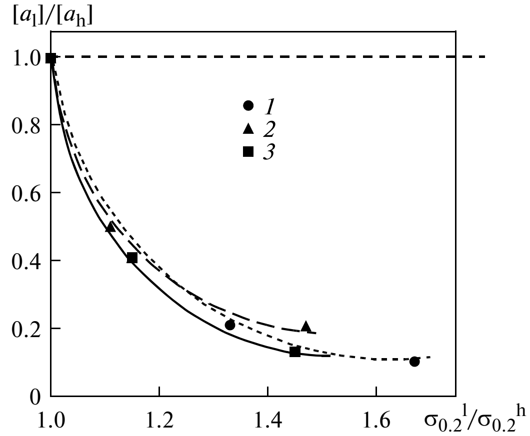
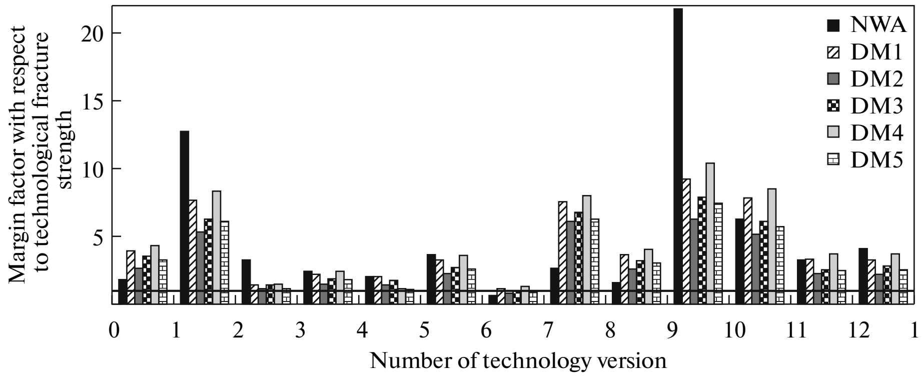


Fig. 3. Reduction of the sizes of permissible flaws vs. the increase in the yield strength of chromium–molybdenum–vanadium steels. (*1*) Grade 12Kh1MF steel, $\sigma_{0.2}^{l}$ = 298 MPa; (*2*) 15Kh1M1F, $\sigma_{0.2}^{l}$ = 360 MPa; (*3*) 25Kh1M1FA, $\sigma_{0.2}^{l}$ = 435 MPa; a_l and a_h are the sizes of permissible flaws for low- and high-strength steels, and $\sigma_{0.2}^{l}$ and σ_h are the low and high yield strength levels.

The use of the developed theoretical and numerical models, methodological principles, fracture criteria, and experimental methods makes it possible to quantitatively analyze a large number of technological alternatives within a short period of time and select the most stable welding technologies application of which ensures the highest safety margins (n_k) with respect to technological resistance to growth of cracks. Figure 4 shows the results from an analysis of technological resistance to crack growth for the versions of surfacing metal to the journals and thrust plates of the high- and intermediate-pressure rotors of a 660-MW steam turbine. A comparison of margin factors with respect to resistance to cold cracks in the near-weld zone of welded connections made of 11% chromium rotor steel [27] was carried out. A total of 68 technological versions were subjected to experimental and calculated studies, and 13 versions giving the highest margins with respect to technological resistance to crack growth were selected from them for further investigation based on the study results. The resistances to hot cracks and cracks due to thermal treatment were estimated in a similar way. The results obtained from determination of safety margins with respect to technological strength are given in [27].



Zone	Rotor journal						Rotor disk						
	Versions												
	1	2	8	9	10	11	3	4	5	6	7	12	13
NWA	1.8	12.8	2.7	1.6	21.8	6.3	3.3	2.4	2.0	3.7	0.6	3.3	4.1
DM1	3.9	7.7	7.5	3.7	9.2	7.8	1.4	2.2	2.0	3.3	1.2	3.4	3.3
DM2	2.7	5.3	6.1	2.6	6.3	5.2	1.2	1.5	1.4	2.3	0.9	2.5	2.6
DM3	3.5	6.3	6.7	3.2	7.9	6.1	1.3	1.9	1.7	2.7	1.0	2.6	2.8
DM4	4.3	8.4	8.0	4.1	10.4	8.5	1.5	2.4	1.2	3.6	1.3	3.7	3.7
DM5	3.3	6.1	6.3	3.0	7.4	5.7	1.2	1.8	1.1	2.6	0.9	2.5	2.6
q, J/mm	460	460	335	670	335	670	335	460	670	460	460	670	335
T_h, °C	150	300	50	150	300	300	150	150	150	300	20	300	300
W_0, °C/c	93	45	127	63	62	31	127	93	63	45	157	31	62

Fig. 4. Summary diagram for drawing up versions of the technological process of surfacing the rotor journal and disk based on the margin factor corresponding to the condition of cold crack development in the near-weld area (NWA) and deposited metal (DM) with different extents of alloying. 1–5 are the numbers of welding materials. $q_{h.r,}$ T_h, and W_0 are the welding heat input, heating temperature, and cooling rate established during the calculated simulation of the surfacing process.

Application of the principles of combined mechanical and process designing makes it possible to construct new power installations within a considerably shorter period of time while ensuring their high reliability and essentially reducing costs for their development.

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