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STRENGTH OF WELDED THICK WALLED NON-HEAT TREATED STRUCTURAL ELEMENTS

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An investigation has been made with a view to estimating the strength and toughness of a hydraulic turbine volute chamber made of welded low-alloy steel sheet, 70 mm thick. The purpose of the work is to assess the risk of failure of this chamber in which weld residual stresses may reach yield stress, σ_Y, level.

The dimensions and construction of the chamber makes it localized and overall heat treatment after welding impossible. For the tests plates 70 mm thick, made of 14GNMA (C-0.15, Si-0.29, Mn-0.9, Cr-0.16, Ni-0.52, Mo-0.33) and 22K (C-0.19, Si-0.27, Mn-0.6, Cr-0.2, Ni-0.31) steels were used. Mechanical properties of these steels are given in Table 1. These plates were welded manually without preheating by "transverse ridge" (TR) and "longitudinal cascade" (LC) methods. The transverse method is characterized by forming the slope ridge through the full thickness of the joint at 35° to the plate plane by transverse electrode motion. The longitudinal cascade method is characterized by only longitudinal electrode motion and by forming a stepped joint. Some plates were tempered at 943 K to compare the properties of untreated and heat-treated welded joints.

The plates were used to make specimens for determination of standard mechanical properties, CT type specimens and large-scale specimens with section 450 x 70 mm for axial tension tests. Notches were made either in the weld metal along the axis of the seam or in the base metal 4 to 6 mm off the straight edge of the weld seam. V-notches from a hole 100 mm in diameter, in specimens intended for tension tests were terminated in slots, 0.2 mm wide and 4 mm deep, made by electro-erosion machining. For comparison, tests were also performed on unwelded specimens made of steel 14GNMA, as well as on plates with welded joints without mechanical stress concentrators. The welded plates were out-of-flat, had welding angular distortion, unmachined rolled surfaces of the base metal and unmachined weld reinforcement.

The test results of CT specimens were processed in conformity with standard requirements [1]. The values of K_C were determined on the basis of the measured breaking force.

Temperature dependences of K_C for TR and LC welds, all indicate advantages of the TR welding method, Figure 1, because the minimum values of K_C in this case exceed those of the LC method by 15 to 30%. It is also seen that both heat treated and non heat treated specimens with welds made by the TR method give a common scatter band for K_C, whereas the LC welding method brings about lower values of K_C in the weld metal without heat treatment as compared with the heat treated state. The temperature dependence of critical COD, δ_c, values calculated in accordance with procedure [2], is shown in Figure 2.

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Large-scale specimens were tested at temperatures from 273 to 315 K in tension in the initial state or after preloading at 323 K. The results of tests of 12 large-scale specimens are given in Table 2. It is evident that with no stress concentrators the strength of plates made of steel 14GNMA and welded by the TR and LC methods approaches the ultimate strength of the base metal. Thus, in specimens 11 and 12 (Table 2) with residual welding stresses and considerable geometric distortion in the welded joint area, the base metal fractured at the transition from the operating section to the grip fillet without reduction of strength and with permanent elongation of 10.5 to 11 pc. At fracture cracks were apparent in the weld joint of these specimens. This indicated that the strength of the base metal and untreated welded joint were identical.

Mechanical stress concentrators essentially affect the test results. Specimens made of base metal, steel 14GNMA with such concentrators, tested at temperatures of 293 K and 269 K, fractured, respectively, at stresses of 1.02 and 0.93σ_y with a total deformation of 0.42 and 0.35% and critical COD of 0.89 and 0.84 mm. The fractures were flat with small shear lips at the surfaces.

Three specimens were made of steel 22 K with notches in the base metal 4 to 6 mm off the fusion line. This steel has satisfactory mechanical properties (see Table 1), however the stress concentrators brought about a decrease in fracture stress. The fracture stresses in the net section were 0.53 and 0.74σ_y, and in the gross section they were less than the operating stresses in the volute chamber. The force-displacement curves were regular, without plastic strain, and the fractures were flat, which is peculiar to brittle fracture at low stresses.

The test results of specimens made of steel 22 K with notches in the heat-affected area indicate that considerable decrease of the strength is possible in a structure made of material known as possessing good welding properties, with rather satisfactory plastic properties, satisfactory impact toughness, but which has high shear texture transition temperature T^{50}_{FATT} = 303 K. This result makes it impossible to recommend steel 22 K for manufacture of the volute chamber.

Large scale specimens with shallow and deep notches in welded seams made by the TR method fractured at 0.83 and 0.8σ_y, respectively, at a total deformation and critical COD which were greater than or equal to the values obtained on plates made of steel 14GNMA without welding with similar notches. Specimens with shallow notches in the weld metal, prestrain at 323 K and gross stresses of 170 MPa (corresponding to stresses in the chamber hydraulic test at 35 atm), fractured at net stresses of 0.85 and 0.93σ_y with total deformation exceeding that of steel 14GNMA at the moment of fracture.

Thus, untreated welded joints with weld reinforcement present and unmachined surfaces of plates with through stress concentrators, 110 to 150 mm long, and deformed by welding made by the TR method fractured at net stresses exceeding 0.8σ_y of the base metal and deformation approximating or even exceeding that of steel 14GNMA. These results together with data obtained on CT specimens indicate quite satisfactory properties of steel 14GNMA. Therefore the possibility exists to recommend steel 14GNMA and welding by the TR method for untreated welded joints to be used for thick-walled articles, such as, for example, volute chambers of hydraulic turbines.

The tests showed (Table 2, Nos. 7, 8, 9 and 10) that under conditions of stress concentration the prestrain of specimens (at 323 K) welded by the TR method leads to an increase of breaking stresses at 269 K and 273 K by 6 and 16%, respectively, and to the increase of total deformation. It is to be supposed that under conditions of stress concentration the strength and strain properties of welded seams, if necessary, can be improved by hydraulic pressurization of thick walled chambers at wall stresses of 170 MPa and temperature of 323 K.

In manufacturing the volute chambers of hydraulic turbines welding defects may be expected. Therefore, it is necessary to determine the dimensions of permissible defects. The strength of structures with defects may be analyzed by linear fracture mechanics methods and the K_{IC} criterion [3]. However, despite the fact that values of K_{IC} for a welded joint are available, the above method cannot be applied to untreated welded joints, where under operating conditions plastic strains may be present to a large extent. Indeed, welding tensile stresses in welded joints of hydraulic turbine volute chambers with walls 70 mm thick, may reach yield stress σ_y = 350 to 460 MPa. The combined actions of working and residual stresses inevitably involve local plastic strain. Therefore, in our case use was made of concepts of fracture mechanics under conditions of general yielding and strain criterion δ_c was used instead of stress criterion K_{IC}.

We based this calculation on curve 1 (Figure 3) showing the dependence of the nondimensional COD

$$\varnothing = \frac{\delta_c}{2\pi \cdot e_y \cdot a}$$

on relative total deformation; the curve was proposed by Burdekin and Dawes [4]. This curve is positioned at the upper boundary of the experimental data shown in the figure by the shaded area which was obtained from tests of low carbon steel plates, 915 x 915 mm, 25 and 75 mm thick, with notches of from 13 to 230 mm. This curve may be used in this case too, since experimental points of tension-tested plates of practically the same thickness (70 mm) made of steel 14GNMA without welding and of plates made of the same steel with seams welded by the TR method correspond to the experimental data of [4].

It is expected in [4] that if residual stresses are present in welded seams of pressure vessel shells, the structure relative total deformation

$$\frac{e}{e_y} = 2.0 ,$$

and the crack dimensionless opening $\varnothing$ = 1.75. Then, in order to determine the half through notch length, use may be made of the following formula:

$$a_{cr} = 0.09 \left(\frac{\delta_c}{e_y}\right) .$$

For metal in the seam made by the TR method, the minimum critical COD at 269 K, δ_c = 0.683 mm, yield stress σ_y = 370 MPa, modulus of elasticity E = 215 GPa and deformation corresponding to the yield stress

$$e_y = \frac{\sigma_y}{E} = 1.75 \cdot 10^{-3} .$$

From these data one half the through notch critical length $a_{cr} = 35$ mm. In case the ratio of the depth of semi-elliptical defect a_e to the thickness exceeds 1/3 and ratio a_e to surface defect length 2b is equal to 0.3, dimension a_e should be equal to a_{cr}, i.e., to half the through notch length [5]. Then, the length of the semi-elliptical defect of critical dimension will be

$$2b = \frac{35}{0.3} = 115 \text{ mm}.$$

Taking into consideration the necessary safety factor to four [5], the permissible depth of the surface semi-elliptical defect should be less than

$$a_o = \frac{35}{4} = 9 \text{ mm},$$

and the length should be less than

$$2b_o = \frac{115}{4} = 29 \text{ mm}.$$

Estimation of the permissible defect dimensions is performed on the basis of data obtained during tests of plates of full-scale thickness with notches having a radius of 0.1 mm at the apex on the assumption that the volute chamber is free from defects such as long cracks.

Permissible dimensions of the defect in this structure may be estimated also on the basis of results of testing specimens for eccentric tension; on these specimens, the minimum value $\delta_c = 0.206$ mm was obtained at a temperature of 269 K in the presence of a fatigue crack in the weld metal. Then, for the same conditions $a_{cr} = 11.8$ mm, $a_e = a_{cr} \cdot Q = 11.8 \times 1.645 = 19.4$ mm and the length of the semi-elliptical defect of critical dimension $2b = 65$ mm. In this case, i.e., when the ratio of the defect depth to the wall thickness is less than 1/3, parameter Q is determined according to the formula [5]:

$$Q = 1 + 4.6 \left(\frac{a_e}{2b}\right)^{1.65}.$$

Thus, in estimating the strength of non-heat treated welded joints as applied to the volute chamber with the use of results of testing eccentric tension specimens permissible surface defects of the semi-elliptical shape at four-fold safety factor may have depth a of less than 5 mm and length 2b not exceeding 16 mm.

Comparison of results obtained by both methods indicates that for higher reliability only the latest data should be used.

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Table 1 Mechanical Properties of Steels 14GNMA and 22K

Steel	T,K	σ_y MPa	σ_{max} MPa	ε_f %	R of a, %	Charpy J/cm²	Shear Strain Prior to Fracture, %
14GNMA	223	390	552	32.3	64.9	-	-
	253	375	536	33.0	65.5	37	12.5
	273	357	516	33.0	64.6	51	21.5
	293	325	498	31.0	67.0	88	61.0
22 K	233	297	493	32.8	56.0	4	2.4
	253	272	474	33.5	54.5	7	8.4
	273	269	460	32.8	55.5	21	18.0
	293	260	440	32.2	55.0	37	36.0

Table 2 Results of Tests of Large-Scale Specimens

No.	Place of Notch	Depth of Notch from Dia. of 100 mm, mm	Test Temp., K	P_{max} kN	σ_f MPa	ε_f on Gage Length of 400 mm, mm	δ_c mm
1	Base Metal, 14GNMA	25	293	70.6	330	1.68	0.895
2	Base Metal, 14GNMA	25	269	70.1	323	1.32	0.84
3	Heat Affected Zone, Steel 22 K	25	269	36.6	175	0.5	0.11
4	Heat Affected Zone, Steel 22 K	25	267	30.0	142	0.44	0.13
5	Heat Affected Zone, Steel 22 K	25	269	42.4	199	0.52	0.154
6	Weld Metal (TR)	25	269	59.8	282	1.55	0.767
7	Weld Metal (TR)	25	273	61.3	287	2.1	0.812
8	Weld Metal (TR)	5	269	69.1	279	3.5	0.683
9	Weld Metal (TR)	5	323* 269	54.7 71.2	225 295	1.75 3.8	- 0.69
10	Weld Metal (TR)	5	323* 273	54.3 79.4	222 325	1.67 5.1	- 1.1
11	Weld Metal (TR)	not	269	104.8	495	42	-
12	Weld Metal (LC)	not	273	105.2	493	45	-

* Prestrain Temperature

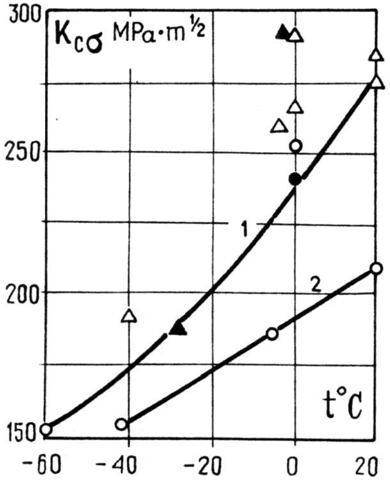

Figure 1 Temperature Dependences $K_{c\sigma}$ of Weld Metal:

▲ - TR Welding with Tempering
△ - TR Welding without Tempering
● - LC Welding with Tempering
○ - LC Welding without Tempering
1 - TR Welding; 2 - LC Welding

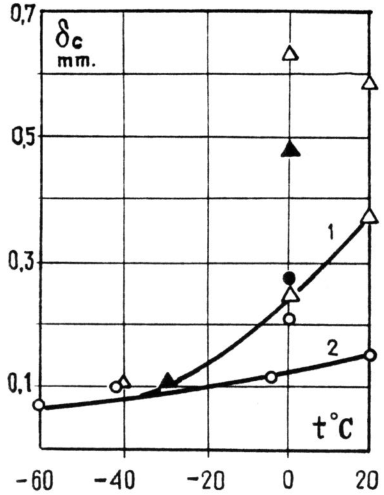

Figure 2 Temperature Dependences δ_c of Weld Metal (Symbols in Figure 1)

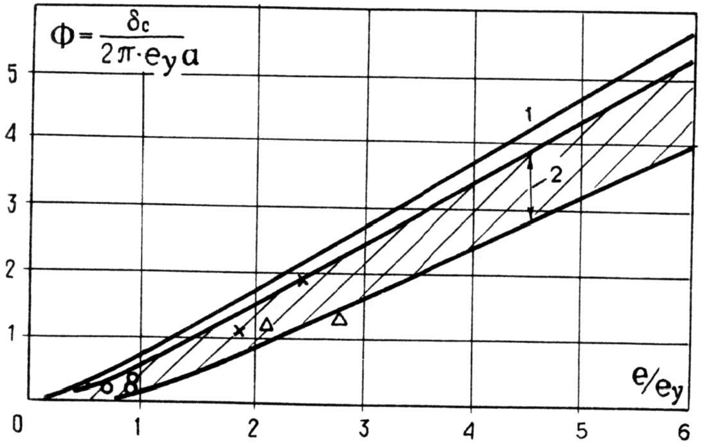

Figure 3 Dependence of COD on Final Total Deformation:

1 - Designed Curves; 2 - Spread of Experimental Points given in [4]; x - Experimental Points Corresponding to Plates 1 and 2; o - Experimental Points Corresponding to Plates 3, 4 and 5; Δ - Experimental Points Corresponding to Plates 6 and 7