MATHEMATICAL FORMULATION OF CARBON EQUIVALENT AS A CRITERION FOR EVALUATION OF STEEL WELDABILITY

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A new criterion is proposed for cold cracking susceptibility of HAZ metal of joints on hardenable steel, based on allowing for the kinetics of austenite decomposition and experimental determination of the incubation period of the start of martensite transformation. It is shown that this criterion can be mathematically reduced to the traditional parameter for assessment of such a weldability of hardenable steels — carbon equivalent. A mathematic dependence of the new criterion on value of carbon equivalent is proposed, which was verified experimentally.

Keywords: *modelling, carbon equivalent, weldability, criteria, cold cracks, diagram of austenite decomposition, martensite, technological tests*

Practice shows that not all of the steels have the same good weldability. One of them can be welded without any limitations. Welding of another requires special technological methods. «Weldability» concept [1–4] has significantly wide interpretation. It should include based on analysis of available works four interdependent factors, i.e. material type, structure type, necessary properties and reliability level [5]. One or another level of weldability is achieved depending on selection and combination of these factors.

Large work on systematization of «weldability» concept and methods of its evaluation was made by K.A. Yushchenko. Thus, he proposed [6, 7] a new understanding of this term based on analysis of existing approaches to evaluation of weldability and standards acting in different countries and organizations. He showed that in most cases the weldability evaluation is qualitative and subjective. This term is considered rather as a philosophical concept and its determination through material capability to form welded joint does not show how and using what it can be measured.

Weldability testing should determine steel appropriateness for welding, but in most cases it is substituted for tests determining susceptibility to formation of various type cracks. Such indices as hot cracking resistance, cold cracking resistance, lamellar cracking and tempering cracking resistance etc. are applied, for example, to carbon and alloyed-steel welded joints.

Results of various welding tests are frequently used for evaluation of weldability of different steels. Tekken, Implant, bead-on-plate, cruciform and Jominy tests are used for determination of cold cracking susceptibility in practice. Holdcroft («fishbone») test or test based on a method of the E.O. Paton Electric Welding Institute is used for evaluation of weld metal hot cracking resistance. «Cranfield» tests, «Window» type test, N-shape test, improved Implant test as well as cruciform test (GOST 28870–90) are applied for lamellar fracture. Circular tests of BWRA, Tekken, Lehigh University, CTS or MRT [5] are used for tempering cracks. Most of these tests are based on determination of external loading applied to the welded joint, which results in fracture or simple crack appearance.

Cold cracks often appear due to steel hardenability in quick cooling and hydrogen saturation of the weld metal and HAZ. They, as a rule, nucleate after welding and surfacing on the expiry of some time (delayed fracture) and propagate in a course of several hours or even days.

Concept of carbon equivalent is used for evaluation of metal tendency to cold cracking susceptibility. A series of indices [8–11] is assumed for application in present time. All of them are true for specific and, at that, sufficiently narrow concentration ranges and speeds of weld metal cooling. Systematization of the indices of carbon equivalent proposed by different authors (Table 1) is given in work [12].

Thus, analysis of works performed shows sufficiently wide range of applied coefficients that is caused by peculiarities of regression formulation of effect of the alloying elements on cold cracking resistance. Impossibility of a direct experimental determination of the carbon equivalent and its comparison with estimated values is a disadvantage of this approach.

Table 1. Coefficients (backward) in indices of carbon equivalent proposed by various authors [12]

No.	Author	Year	C	Mn	Si	Cu	Ni	Cr	Mo	Nb	V	B
1	IIW	1967	1	6	–	15	15	5	5	–	5	–
2	Ito, Bessyo	1968	1	20	30	20	60	20	15	–	10	1/5
3	Ito, Bessyo	1968	1	20	25	20	40	10	15	–	10	–
4	Stout	1976	1	6	–	40	20	10	10	–	–	–
5	Graville	1976	1	16	–	–	50	23	7	8	9	–
6	Harasawa	1977	1	6	–	15	15	5	5	–	5	–
7	Duren	1980	1	16	25	16	50	20	40	–	13	–
8	Yurioka	1982	1	6	24	13	40	6	4	5	5	1/10
9	Yurioka	1980	1	6	30	15	20	4	6	–	–	–
10	Yurioka	1981	1	6	24	15	20	5	5	5	5	1/5
11	Duren	1982	1	8	11	9	17	5	6	–	3	–
12	Terasaki	1984	1	3	–	4	8	10	3	–	–	1/5
13	Cottrell	1984	1	6	–	–	–	5	5	4×C	3	–
14	Suzuki	1985	1	6	24	15	15	5	5	–	3	1/15
15	Yurioka	1987	1	6	24	15	12	8	4	–	–	–
16	Yurioka	1987	1	5	24	10	18	5	2.5	3	3	–
17	Yurioka	1987	1	3.6	–	20	9	5	4	–	–	–

Aim of the present paper is correlation of the proposed mathematical formulation of criterion of steel weldability with the carbon equivalent and its experimental verification.

It is well known fact that cold cracks appear in HAZ metal under three conditions, i.e. formation of hardening microstructures, presence of diffusible hydrogen, and tensile stresses. Hypothesis that the weldability can be evaluated on index determining what minimum critical time of cooling is necessary for formation of 100 % of martensite in the weld metal makes a basis of mathematical approach for formulation of the carbon equivalent. Indices of 50 or 90 % of martensite formation are traditionally used for evaluation of the steel weldability. Index of critical time of formation 100 % of martensite is used in the present paper because of its sufficiently obvious position in a thermal-kinetics diagram of austenite decomposition (Figure 1).

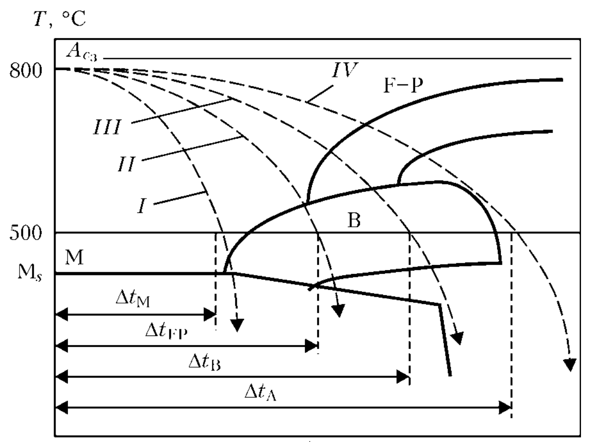

Figure 1. Determination of critical time of cooling in formation of martensite, bainite and ferrite-pearlite structures

Calculation of the carbon equivalent is based on additivity rule [13]. It is assumed that τ is some incubation (preparation) period depending on temperature and chemical composition of the material and showing that transformation has not yet started. Part of the incubation time in each step is expressed as dt/τ function if cooling curve in welding is divided on separate sections of dt duration. If transformation is completely finished then 1 will be obtained after integration of all these dt/τ parts. Besides, such an approach is sometimes used for transformation of TTT-diagram in CCT-diagram of austenite decomposition.

Criterion at which transformation does not take place is expressed in the following way:

$$\int_0^{t_e} \frac{dt}{\tau} \le 1. \qquad (1)$$

Thus, the transformation finishes when the left part of equation (1) equals not more than 1 and structure of steel makes 100 % martensite.

Critical time of cooling, at which value of the left part equals 1, in integration from $t = 0$, when the weld temperature achieves $T = A_{l_3}$ point, up to $t = t_e$ at $T = M_s$ at which martensite transformation start, can be determined using this equation.

Figure 1 shows the cooling curve I when equation (1) equals 1. Position of curve I in Figure 1 corresponds to the critical time of cooling, at which HAZ structure consists of 100 % martensite. This means that speed of cooling from 800 up to 500 °C along the curve I of austenite cooling determines the critical time of cooling Δt_{M}. If incubation time τ is set as a function of steel chemical composition then the carbon equivalent can be determined with the help of equation (1). Besides, if the formulae will include τ dependences on other factors (for example, size of austenite grain) then the level of their influence on carbon equivalent can be evaluated that is not considered in the most cases.

Perform modification of equation (1) in order to determine an effect of chemical composition on Δt_{M}:

$$\int_0^{t_e} \frac{dt}{\tau} = \int_{A_{e3}}^{\mathrm{M_s}} \frac{1}{\tau}\left(\frac{dt}{dT}\right) dT = 1, \quad \frac{dt}{dT} \approx \frac{\Delta t_{\mathrm{M}}}{300}, \tag{2}$$

$$\Delta t_{\mathrm{M}} = 300 / \int_{A_{e3}}^{\mathrm{M_s}} \frac{dT}{\tau}. \tag{3}$$

Equation below helps to evaluate HAZ metal hardenability:

$$\ln(\Delta t_{\mathrm{M}}) = A \cdot CE_{\mathrm{M}} + B, \tag{4}$$

where A, B are the constants, and M is the index relating to martensite. Considering expression (3) equation (4) will have the following form:

$$\ln(\Delta t_{\mathrm{M}}) = \ln(300) - \ln\left(\int_{A_{e3}}^{\mathrm{M_s}} \frac{dT}{\tau}\right). \tag{5}$$

It can be seen from matching of equations (4) and (5) that the carbon equivalent corresponds to linear term. The latter can be obtained if the second term of equation (5) is expanded in Taylor's series on each element:

$$A_X = \frac{\partial}{\partial X}\left[\ln\left(\int_{A_{e3}}^{\mathrm{M_s}} \frac{dT}{\tau}\right)\right],$$

where X = (C, Si, Mn, Mo etc.).

Then the carbon equivalent can be expressed as

Table 2. Comparison of calculation coefficients (equation 11) of carbon equivalent with literature data

Element	A_X	A_X/A_c	IIW [9]	Ito [10]	Yurioka [17]
C	–3.02	1	1	1	1
Si	–0.08	1/38	1/24	1/25	1/24
Mn	–0.50	1/6	1/6	1/20	1/6
Ni	–0.25	1/12	1/15	1/40	1/12
Cr	–1.64	1/1.8	1/5	1/10	1/8
Mo	–1.30	1/2.3	1/5	1/15	1/4
Cu	–0.33	1/9.1	1/15	1/20	1/15
V	–	–	1/5	1/10	–

$$\begin{gathered}\ln(\Delta t_{\mathrm{M}}) = \ln(300) - \{A_{\mathrm{C}}(\mathrm{C} - \mathrm{C}_0) + \\ + A_{\mathrm{Si}}(\mathrm{Si} - \mathrm{Si}_0) + A_{\mathrm{Mn}}(\mathrm{Mn} - \mathrm{Mn}_0) + \ldots\} = \\ = \mathrm{C}_0 - A_{\mathrm{C}} CE_{\mathrm{M}}.\end{gathered} \tag{6}$$

Matching of the left and right sides of equation (6) gives

$$\begin{gathered}\mathrm{C}_0 = \ln(300) A_{\mathrm{C}}\mathrm{C}_0 + A_{\mathrm{Si}}\mathrm{Si}_0 + A_{\mathrm{Mn}}\mathrm{Mn}_0 + \ldots, \\ CE_{\mathrm{M}} = \mathrm{C} + \frac{A_{\mathrm{Si}}}{A_{\mathrm{C}}}\mathrm{Si} + \frac{A_{\mathrm{Mn}}}{A_{\mathrm{C}}}\mathrm{Mn} + \ldots,\end{gathered} \tag{7}$$

where C_0, M_0, Mn_0 etc. are the concentrations corresponding to concentrations at which Taylor's series is hold; CE_{M} is the expression for the carbon equivalent that can be calculated.

Expressions for τ, A_{e3} and $\mathrm{M_s}$ are to be known for determining CE_{M} using equation (7). Expressions proposed in works [14, 15] were taken for this:

$$\begin{gathered}\tau = \frac{\exp(83500/RT)}{2^{N/8}(A_{e3} - T)^3} \times \\ \times (60\mathrm{C} + 90\mathrm{Si} + 160\mathrm{Cr} + 200\mathrm{Mo}),\end{gathered} \tag{8}$$

$$\begin{gathered}A_{e3} = 1185 - 203\sqrt{\mathrm{C}} = 15.2\mathrm{Ni} + 44.7\mathrm{Si} + 104\mathrm{V} + \\ + 13.5\mathrm{Mo} + 13.1\mathrm{W} - 30\mathrm{Mn} - 11\mathrm{Cr} - 20\mathrm{Cu} + \\ + 700\mathrm{P} + 400\mathrm{Al} + 120\mathrm{As} + 400\mathrm{Ti},\end{gathered} \tag{9}$$

$$\begin{gathered}\mathrm{M_s} = 831 - 474\mathrm{C} - 33\mathrm{Mn} - 17\mathrm{Ni} - \\ - 17\mathrm{Cr} - 21\mathrm{Mo}.\end{gathered} \tag{10}$$

T is the temperature, °C; N is the grain number on ASTM; R = 8.31 J/(mole·K) is the gas constant in the equations given above.

The coefficients for a point about which Taylor's series expansion is carried out, i.e. C_0 = = 0.46; Si_0 = 0.23; Mn_0 = 0.78; Ni_0 = 0.27; Cr_0 = = 0.26; Mo_0 = 0.1; Cu_0 = 0.1, were obtained in works [14, 16].

As a result the equation for carbon equivalent is transformed in the following way:

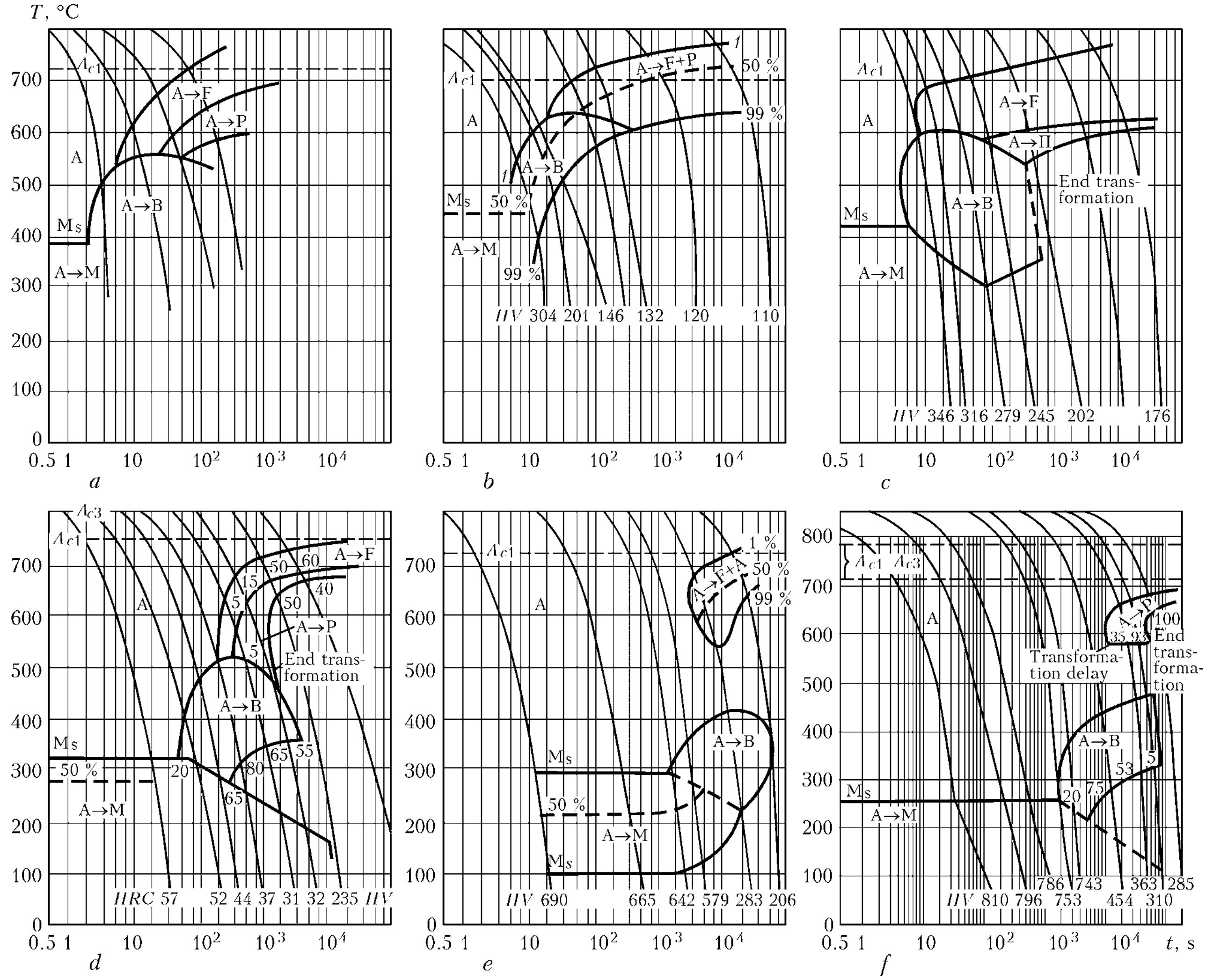

Figure 2. Thermal-kinetic diagrams of austenite decomposition of investigated steels [18]: *a* — 17G1S; *b* — 10G2S; *c* — 16G2AF; *d* — 35KhM; *e* — 35KhGSM; *f* — 50KhNM

Table 3. Chemical composition and temperatures of transformation points of investigated steels

Steel grade	Weldability	Chemical composition of steels, wt.%						
		C	Si	Mn	Cr	V	Mo	Ni/B
17G1S	Good	0.17	0.60	1.48	–	–	–	–
10G2S	Same	0.08	0.35	1.45	–	–	–	0.006
16G2AF	Satisfactory	0.17	0.36	1.44	–	0.11	–	–
35KhM	Limited	0.37	0.30	0.79	1.0	–	0.18	–
35KhGSM	Bad	0.39	1.49	1.41	0.74	–	0.51	–
50KhNM	Same	0.52	0.29	–	1.09	0.14	0.43	1.72

Table 3. (cont.)

Steel grade	Weldability	Temperature, °C				Δt_M, s	CE_M, % (IIW)
		A_{c1}	A_{c3}	M_s	T_s		
17G1S	Good	730	–	390	1130	2	0.44
10G2S	Same	700	850	440	880	4	0.37
16G2AF	Satisfactory	700	830	425	950	6	0.45
35KhM	Limited	750	–	320	850	60	0.75
35KhGSM	Bad	725	857	290	885	2000	0.94
50KhNM	Same	710	790	260	950	2000	0.98

$$CE_M = C + \frac{1}{38}Si + \frac{1}{6}Mn + \\ + \frac{1}{12}Ni + \frac{1}{1.8}Cr + \frac{1}{2.3}Mo + \frac{1}{9.1}Cu. \quad (11)$$

Table 2 shows the results of calculation of coefficients in the carbon equivalent equation and their correspondence to literature data. Analysis of the results shows good correspondence of the calculated coefficients to the coefficient proposed by IIW and Yurioka et al.

Thus, an approach proposed for the weldability evaluation on cold cracking susceptibility is verified mathematically, on the one side, and have understandable physical meaning, on the other side. It is based on evaluation of the critical time necessary for 100 % martensite transformation. It may sound strange, but the ideas is that the lower is the preparatory time necessary for 100 % martensite structure formation (i.e. the higher the critical speed of cooling) the better is weldability and higher is cold cracking resistance. This indicates that preparatory processes related with the cold crack formation have kinetic (diffusion) character and directly connected with redistribution of hydrogen in the weld metal. Hydrogen is quickly fixed in the weld metal in the case of short (1–10 s) incubation period of martensite formation, however, its local concentration appears to be not sufficient for initiation of cold cracking. If the incubation period of martensite formation is long (1000–2000 s) the time is found to be enough for hydrogen embrittlement of the metal being welded. Gradual redistribution of the hydrogen is possible at short incubation period and further long-term soaking depending on type of formed microstructure, that result in delayed fracture effect.

In conclusion assumed by us hypothesis (equitation (4)) will be checked experimentally. Steels proceeding from their weldability, i.e. steels 17G1S, 10G2S of good weldability, 16G2AF steel of satisfactory weldability, 35KhM steel of limited weldability and 35KhGSM, 50KhNM steels of bad weldability [19] were taken for this purpose. Figure 2 shows the thermal-kinetic diagrams of austenite decomposition of these steels. Chemical composition and character temperatures of the critical points are given in Table 3.

Analysis of results of Table 3 and Figure 3 showed that the dependence proposed in equation (4) is valid. Coefficients $A = 11.26$ and $B = -3.51$ of the equation (4) were determined experimentally. Present coefficients have good correspondence with the equation for numerical evaluation

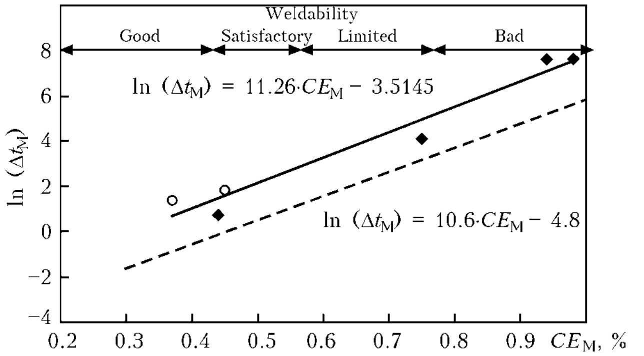

Figure 3. Influence of carbon equivalent of steels considered on function of time of martensite transformation start: points — experimental values; solid line — calculated; dashed — curve from work [20]

of weldability of low-alloyed steels assumed in work [20] and some variance is explained by difference in formulae, taken for the carbon equivalent calculation.

Advantage of the proposed criterion for evaluation of the steel weldability lies, on the one side, in the fact that it can be determined immediately during the experiment and, on the other side, technological peculiarities of welding (method and mode of welding) as well as its metallurgical parameters (chemical composition, influence of welding wire, flux or shielding gas, influence of additive and alloying elements, nonmetallic inclusions etc.) are already considered in the thermal-kinetic diagram of austenite decomposition.

Thus, proposed new criterion of the steel weldability evaluation can be mathematically reduced to the carbon equivalent which is a traditional parameter of steel weldability evaluation. Proposed mathematical dependence of new criterion on carbon equivalent was verified in experimental way.

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INFLUENCE OF DEPOSITED METAL COMPOSITION ON STRUCTURE AND MECHANICAL PROPERTIES OF RECONDITIONED RAILWAY WHEELS

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Experimental data are given on the effect of composition of cladding consumables on formation of structure and mechanical properties of the deposited metal on wheels of steel 2. Strength properties, ductility and crack resistance of railway wheels repaired by cladding, were evaluated by analytical methods. It was found that to ensure the required combination of mechanical properties and high crack resistance of the base and deposited metals it is rational to apply cladding consumables of bainitic or bainitic-martensitic grade for repair of railway wheels of steel 2 by arc cladding.

Keywords: *arc welding, railway wheels, deposited metal, HAZ, structure, properties, crack resistance*

The problem of ensuring the reliability and fatigue life of rolling stock is becoming ever more urgent with increase of transportation volume and traffic intensity of railway transport. It is the most acute for basic parts and mechanisms of bogies of carriages and locomotives, the main part of which is the wheel, directly contacting the rail. Wheel tread wears in service. Flange inner surface is prone to considerable wear that is determined by service conditions of friction-rolling wheel–rail pair. Reconditioning of worn wheel tread is performed in specialized repair plants of railway transport by the method of mechanical turning, or by first performing repair cladding of flange surface.

Railway wheels of freight transport, locomotive wheel flanges, flanges of tram wheels of passenger transport are made of high-strength carbon steels, the composition and mechanical properties of which are given in Tables 1 and 2. As is seen, wheel steels feature high strength and hardness. Such metal properties ensure the required level of service strength of wheels. Flanges and all-rolled wheels from steel 2 are the most widely applied in railway transport of Ukraine and CIS countries. In keeping with GOST 10791–89, carbon content in wheel steel 2 is equal to 0.55–0.65 %. However, as shown by experience

Table 1. Composition of high-strength wheel steels, wt.%

Normative document	Steel grade	C	Mn	Si	V	S	P
						not more than	
GOST 10791–89	1	0.44–0.52	0.80–1.20	0.40–0.60	0.08–0.15	0.030	0.035
GOST 10791–89	2	0.55–0.65	0.50–0.90	0.22–0.45	≤0.10	0.030	0.035
TU U 35.2-23365425-600:2006	T	0.58–0.67	0.70–0.90	≤0.40	0.08–0.15	0.020	0.025