steel castings; another one is to lower phosphorus content. In order to prevent cracks in manganese steels the recommended phosphorus content should be less than 0.02 wt.% [4, 5].

CONCLUSIONS

1. In manufacture of rail frogs by flash-butt welding low-melting intergranular interlayers of phosphide eutectics causing cracking, can form at the distance of 1.5–2.5 mm from the joint line in the HAZ metal of 110G13L steel.

2. Formation of intergranular interlayers of phosphide eutectics at phosphorus content of 0.033–0.036 wt.% is caused by segregational heterogeneity of its distribution at solidification of castings.

3. To prevent formation of intergranular interlayers of phosphide eutectics in the HAZ of 110G13L steel it is necessary to strictly follow the established mode of homogenizing annealing of castings from 110G13L steel.

1. *TU U DP 32-4520.13.500-007-2002:2006*: Crossing and frogs with welded rail ends of R65, R50 and USC60 type with and without insert. Test batch. Valid from 01.01.2003 to 01.01.2006.
2. Kuchuk-Yatsenko, S.I., Shvets, Yu.V., Dumchev, E.A. et al. (2005) Flash butt welding of railway frogs with rail ends using an intermediate insert. *The Paton Welding J.*, **1**, 2–4.
3. Ershov, G.S., Poznyak, L.A. (1998) *Formation of structure and properties of steels and alloys*. Kiev: Naukova Dumka.
4. Kondratyuk, S.E., Kasatkin, O.G. (1987) *Fracture of cast manganese steel*. Kiev: Naukova Dumka.
5. Goudremont, E. (1960) *Special steels*. Vol. 2. Moscow: Metallurgizdat.

PROBABILISTIC CHARACTERISTICS OF HIGH-CYCLE FATIGUE RESISTANCE OF STRUCTURAL STEEL WELDED JOINTS

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Issues of probabilistic determination of resistance of welded joints to high-cycle fatigue fracture are considered. The probability of failure-free performance of the joints for different types and variable values of applied loads is analysed.

Keywords: *welded joints, cyclic loading, high-cycle fatigue, fatigue resistance, probabilistic prediction methods, safe operation*

The growth of interest has been noted lately in probabilistic methods for estimation of beginning of the limiting state of welded joints under different loads, this being associated to a substantial degree with a large number of factors taking place within the joining zone and affecting the beginning of the limiting state. This is particularly important for alternating loads and fatigue fractures of welded joints. The presence of many factors, which are hard to describe in deterministic expressions, leads to a wide spread of data of fatigue tests of the welded joints.

The use of stochastic methods for calculation of fatigue of the welded joints requires clear ideas of the probabilistic characteristics of fatigue fracture resistance of welded joints on different structural materials. Such characteristics for certain welded joints and materials (mainly structural steels) in the form of a range of variations of normal rated stresses, $\Delta\sigma$, and probability of fracture were obtained experimentally [1–3, etc.].

The efforts of the International Institute of Welding (IIW) [4], dedicated to high-cycle fatigue of welded joints on ferritic-pearlitic structural steels with strength of up to 900 MPa showed that at failure probability $Q_p = 5\cdot10^{-2}$ (no-fracture probability is $9.5\cdot10^{-1}$) the fatigue fracture resistance can be sufficiently reliably described by rated stress ranges *FAT* on a base of $N = 2\cdot10^6$ cycles. In this case, the permissible ranges under regular cyclic loading are determined by the following relationship [4]:

$$[\Delta\sigma] = FAT\,\frac{f_1(N)f_2(R)}{\gamma_m f_3(\delta)}, \qquad (1)$$

where $f_1(N)$, $f_2(R)$ and $f_3(\delta)$ are the corrections for durability N, cycle asymmetry R and thickness δ of a workpiece welded (at $N < 2\cdot10^6$ cycles, $R \geq 0.5$ and $\delta > 25$ mm, each of these corrections is more than 1); γ_m is the safety factor equal to 1.0–1.4, i.e. at $f_1 = f_2 = f_3 = 1$ and $\gamma_m = 1$ the failure probability is guaranteed at a level of approximately 0.05.

Naturally, safety grows at $\gamma_m > 1$, and the failure probability dramatically decreases as a result of fatigue fracture.

Considering the IIW recommendations [4], it is of high practical interest to supplement them with the data on fracture probability for different *FAT* values and classes K_x of the joints, depending on the required value of durability N and load level $\Delta\sigma$. For this purpose it is possible to use the already published experimental results on fracture probability of different types of the welded joints, by relating these data to the recommendations given in [4]. The search for

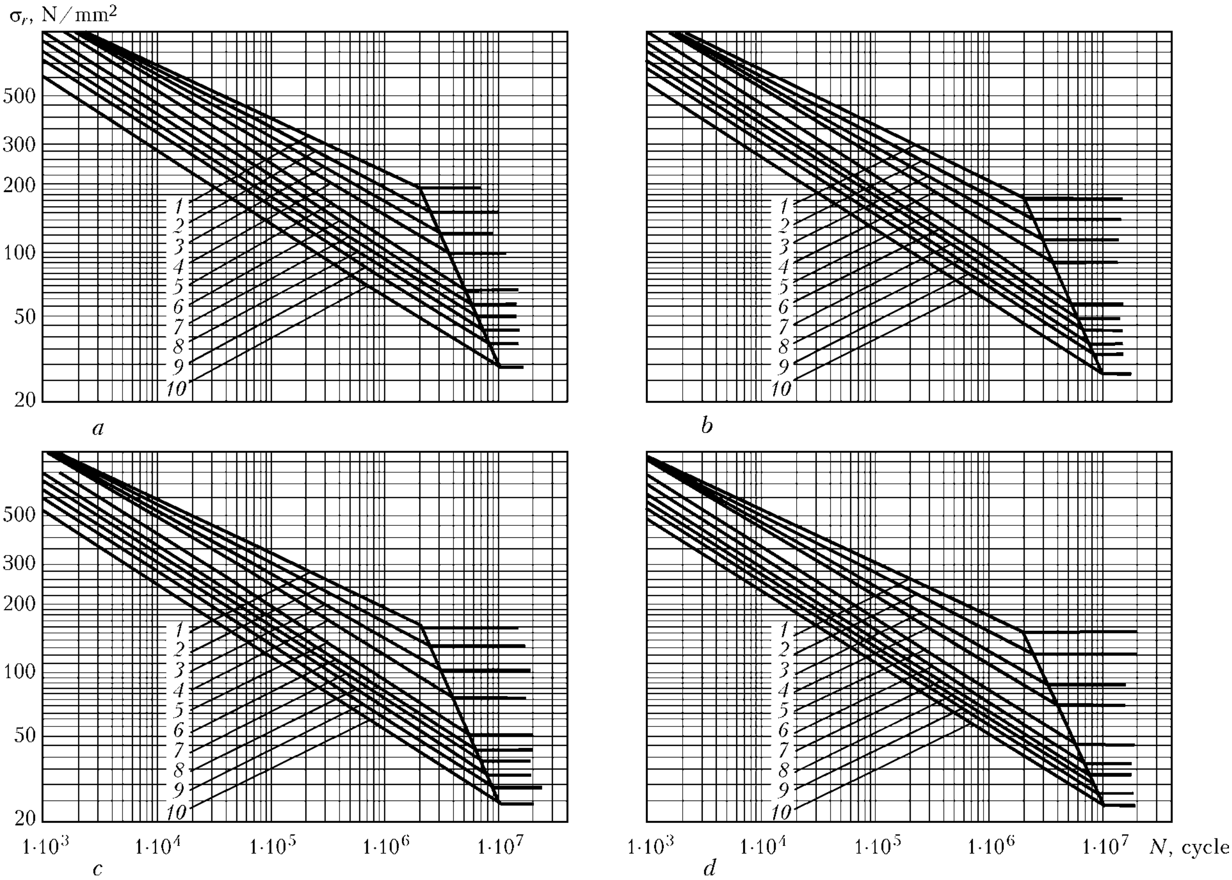

Figure 1. Experimental data [5] on fatigue resistance of different types of welded joints at failure probability $Q_p = 1\cdot10^{-2}$ (*a*), $1\cdot10^{-3}$ (*b*), $1\cdot10^{-4}$ (*c*), $1\cdot10^{-5}$ (*d*) and at K_x = 1.3 (*1*), 1.5 (*2*), 1.7 (*3*), 2.0 (*4*), 2.3 (*5*), 2.6 (*6*), 3.0 (*7*), 3.5 (*8*), 4.0 (*9*) and 5.0 (*10*)

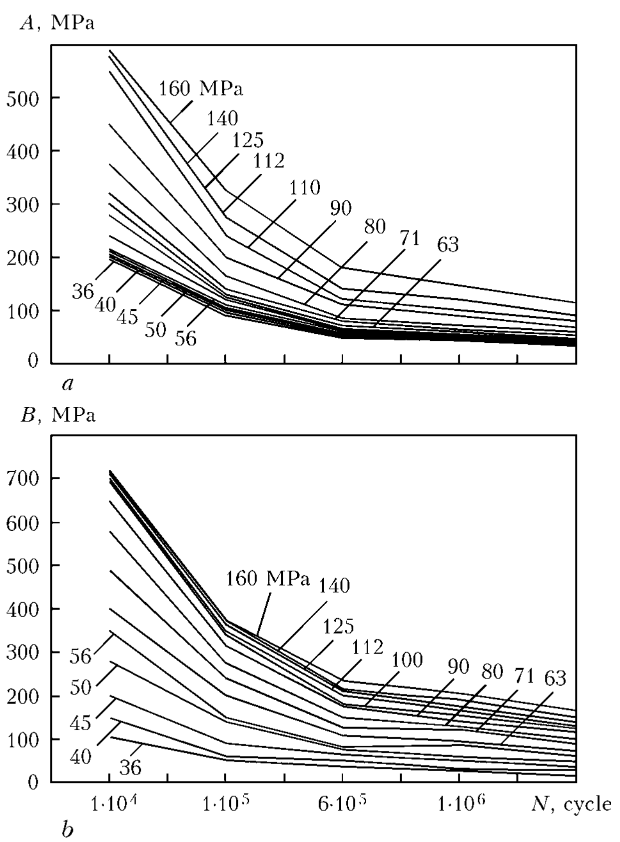

Figure 2. Weibull equation parameters *A* (*a*) and *B* (*b*) versus durability *N* and class of a joint from 36 to 160 MPa

the corresponding published data led to a publication of the manual by Swedish Company «Svenkt Stal» in 1987, dedicated to design (strength calculation) of weldments of extra high-strength (EHS) and abrasion-resistant (AR) steels for equipment of the type of excavating machines, dump trucks, mining, felling and other machines [5]. The steels (especially EHS) correspond in full to those described in [4], and the set of the welded joints in [5] also corresponds to that considered in [4]. However, the classification employed is different. A class of the joint in [5] is determined by ratio $K_x = 315/\sigma_r$, where σ_r is the maximal stress at $R = 0$, i.e. $\sigma_r \approx \Delta\sigma$. Figure 1 and Table 1 give data on different values of failure probability Q_p, K_x, durability N and $\sigma_r = \Delta\sigma$ at $R = 0$, this corresponding to

$$\sigma_r = FAT f_2(R) f_4(Q_p), \tag{2}$$

where f_2 is the correction for cycle asymmetry coefficient R according to [4] at $R = 0$; $f_2(R) = 1.2$; and $f_4(Q_p)$ is the correction related to probability Q_p other than 0.05, corresponding to *FAT* according to [4].

To describe Q_p, we suggest using the three-parameter Weibull law in the form of

$$Q_p = \left(\frac{\Delta\sigma - A}{B}\right)^{\eta}, \tag{3}$$

Table 1. Maximal stress σ_r (N/mm^2) according to [5]

N, cycle	K_x									
	1.3	1.5	1.7	2.0	2.3	2.6	3.0	3.5	4.0	5.0
$Q_p = 1\cdot10^{-2}$										
$1\cdot10^3$	900	900	900	900	900	900	900	800	720	600
$1\cdot10^4$	690	680	620	580	540	460	420	370	340	280
$1\cdot10^5$	400	350	325	290	245	220	195	175	160	135
$6\cdot10^5$	260	220	195	170	138	120	110	100	87	74
$1\cdot10^6$	220	190	168	142	115	103	92	83	75	62
$2\cdot10^6$	185	160	138	115	93	80	73	65	58	48
$Q_p = 1\cdot10^{-3}$										
$1\cdot10^3$	900	900	900	900	900	856	781	705	655	554
$1\cdot10^4$	636	598	559	529	450	398	362	327	304	257
$1\cdot10^5$	357	321	289	258	209	184	168	152	141	119
$6\cdot10^5$	228	197	176	147	115	101	93	84	78	66
$1\cdot10^6$	201	172	149	125	97	86	78	71	66	55
$2\cdot10^6$	169	143	123	101	77	68	62	56	52	44
$Q_p = 1\cdot10^{-4}$										
$1\cdot10^3$	900	900	900	900	900	800	710	650	600	520
$1\cdot10^4$	600	560	520	490	410	360	340	300	280	240
$1\cdot10^5$	340	300	270	240	190	170	158	140	130	112
$6\cdot10^5$	215	185	160	137	107	95	87	78	70	63
$1\cdot10^6$	185	160	140	115	87	80	73	65	58	53
$2\cdot10^6$	160	135	114	94	70	64	57	52	47	42
$Q_p = 1\cdot10^{-5}$										
$1\cdot10^3$	900	900	900	900	781	692	642	592	554	491
$1\cdot10^4$	557	514	481	450	363	322	298	275	257	228
$1\cdot10^5$	312	276	249	219	168	149	138	128	119	106
$6\cdot10^5$	199	170	150	125	93	82	76	70	66	58
$1\cdot10^6$	176	148	129	107	78	69	64	59	55	49
$2\cdot10^6$	148	123	106	86	62	55	51	47	44	39

Table 2. Comparison of experimental data of Table 1 with calculated ones (3) for σ_r (MPa) at $N = 2\cdot10^6$ cycle and mean values of parameters A and B

Q_p	K_x									
	1.3	1.5	1.7	2.0	2.3	2.6	3.0	3.5	4.0	5.0
$1\cdot10^{-2}$	$\frac{185}{192}$	$\frac{160}{166}$	$\frac{138}{141}$	$\frac{115}{120}$	$\frac{93}{95}$	$\frac{80}{84}$	$\frac{73}{75}$	$\frac{65}{67}$	$\frac{58}{60}$	$\frac{48}{50}$
$1\cdot10^{-3}$	$\frac{169}{170}$	$\frac{143}{145}$	$\frac{123}{124}$	$\frac{101}{102}$	$\frac{77}{78}$	$\frac{68}{70}$	$\frac{62}{63}$	$\frac{56}{57}$	$\frac{52}{52}$	$\frac{44}{44}$
$1\cdot10^{-4}$	$\frac{160}{158}$	$\frac{135}{133}$	$\frac{114}{113}$	$\frac{94}{93}$	$\frac{70}{69}$	$\frac{64}{62}$	$\frac{57}{56}$	$\frac{52}{51}$	$\frac{47}{47}$	$\frac{42}{41}$
$1\cdot10^{-5}$	$\frac{148}{151}$	$\frac{123}{126}$	$\frac{106}{108}$	$\frac{86}{87}$	$\frac{62}{63}$	$\frac{55}{57}$	$\frac{51}{52}$	$\frac{47}{48}$	$\frac{44}{45}$	$\frac{39}{40}$

Note. The data according to [5] are given in numerator, and those calculated from (3) are given in denominator.

Table 3. Failure probability Q_p and corresponding values of safety factor γ_m for $N = 2\cdot10^6$ cycle at $R = 0$

K_x	FAT, MPa	$Q_p = 5\cdot10^{-2}$		$Q_p = 1\cdot10^{-2}$		$Q_p = 1\cdot10^{-3}$		$Q_p = 1\cdot10^{-4}$		$Q_p = 1\cdot10^{-5}$	
		$\Delta\sigma$, MPa	γ_m	$\Delta\sigma$, MPa	γ_m	$\Delta\sigma$, MPa	γ_m	$\Delta\sigma$, MPa	γ_m	$\Delta\sigma$, MPa	γ_m
1.7	135	161.9	1.0	138	1.17	123	1.32	114	1.42	106	1.53
2.0	116	139.5	1.0	115	1.21	101	1.38	94	1.48	86	1.62
2.3	95	114.6	1.0	93	1.23	77	1.49	70	1.64	62	1.85
2.6	84	100.6	1.0	80	1.26	68	1.48	64	1.58	55	1.83
3.0	74	89.00	1.0	73	1.22	62	1.43	57	1.56	51	1.74
3.5	65	78.00	1.0	65	1.20	56	1.39	52	1.50	47	1.66
4.0	58	68.70	1.0	58	1.18	52	1.32	47	1.46	44	1.56
5.0	46	55.60	1.0	48	1.16	44	1.26	42	1.32	39	1.42

Table 4. Examples of calculation of durability of weldments with 15 welded joints for different N

FAT, MPa	A, MPa	B, MPa	n	$\Delta\sigma$, MPa	$Q(1)$	$Q(n)$
$N = 2\cdot10^6$ cycle						
71	44	88	5	70	$7.59\cdot10^{-3}$	$3.79\cdot10^{-2}$
63	42	73	5	60	$3.68\cdot10^{-3}$	$1.84\cdot10^{-2}$
45	36	36	2	50	$2.26\cdot10^{-2}$	$4.52\cdot10^{-2}$
36	32	15	3	40	$7.77\cdot10^{-2}$	$2.33\cdot10^{-1}$
						$\Sigma Q_p = 2.84\cdot10^{-1}$
$N = 1\cdot10^6$ cycle						
71	55	120	5	70	$2.44\cdot10^{-4}$	$1.22\cdot10^{-3}$
63	52	95	5	70	$1.29\cdot10^{-3}$	$6.44\cdot10^{-3}$
45	46	49	2	60	$6.64\cdot10^{-3}$	$1.33\cdot10^{-2}$
36	43	25	3	45	$4.09\cdot10^{-5}$	$1.23\cdot10^{-4}$
						$\Sigma Q_p = 2.1\cdot10^{-2}$
$N = 6\cdot10^5$ cycle						
71	65	125	5	80	$2.07\cdot10^{-4}$	$1.03\cdot10^{-3}$
63	62	108	5	80	$7.71\cdot10^{-4}$	$3.85\cdot10^{-3}$
45	53	64	2	70	$4.96\cdot10^{-3}$	$9.93\cdot10^{-3}$
36	48	35	3	60	$1.37\cdot10^{-2}$	$4.12\cdot10^{-2}$
						$\Sigma Q_p = 5.44\cdot10^{-2}$
$N = 1\cdot10^5$ cycle						
71	125	240	5	140	$1.52\cdot10^{-5}$	$7.63\cdot10^{-5}$
63	120	200	5	140	$9.99\cdot10^{-5}$	$5.00\cdot10^{-4}$
45	100	90	2	110	$1.52\cdot10^{-4}$	$3.05\cdot10^{-4}$
36	90	50	3	100	$1.60\cdot10^{-3}$	$4.79\cdot10^{-3}$
						$\Sigma Q_p = 5.66\cdot10^{-3}$
$N = 1\cdot10^4$ cycle						
71	280	490	5	310	$1.40\cdot10^{-5}$	$7.02\cdot10^{-5}$
63	240	400	5	270	$3.16\cdot10^{-5}$	$1.58\cdot10^{-4}$
45	205	200	2	220	$3.16\cdot10^{-5}$	$6.33\cdot10^{-5}$
36	195	105	3	210	$4.16\cdot10^{-4}$	$1.25\cdot10^{-3}$
						$\Sigma Q_p = 1.54\cdot10^{-3}$

Note. n — quantity of joints of the same type at preset FAT; $Q(1)$ — failure probability for one joint; $Q(n)$ — failure probability for at least one of the n joints of the same type; ΣQ_p — failure probability for at least one of the joints in a weldment.

where $\Delta\sigma > A$. Here A, B and η are the law parameters depending on K_x (or FAT) and N. They can be determined from the data given in Table 1. Good agreement was achieved at $\eta = 4$. The calculations of the values of A and B depending on durability N and class of a joint FAT are shown in Figure 2.

Consider the degree of agreement of the calculation of Q_p from (2) with the experimental data of Table 1 by using the above relationship between K_x and FAT in the following form:

$$FAT(K_x) = \sigma_r(K_x,\ Q_p = 5\cdot10^{-2},\ N = 2\cdot10^6)/1.2, \quad (4)$$

as well as the data of Table 1 and relationship (3).

The results obtained are given in Table 2. They show that the experimental data according to [5] for σ_r from Table 1 and the calculated data based on (3) at different values of parameters A and B at $Q_p = 1\cdot10^{-2}$, $1\cdot10^{-3}$, $1\cdot10^{-4}$ and $1\cdot10^{-5}$ are in sufficiently good agreement.

Of special interest is the question how the calculation based on the permissible fracture probability agrees with the calculation based on the preset value of safety factor $\gamma_m = 1.0$–1.4 recommended in [4]. Table 3 gives such data obtained for welded joints with different values of K_x [5] and corresponding FAT [4] for durability $N = 2\cdot10^6$ cycles at cycle asymmetry coefficient $R = 0$.

It can be seen from Table 3 that a relatively small variation in γ_m has a dramatic effect on the Q_p values, i.e. at the reasonable risks of failure within $Q_p = 1\cdot10^{-4}$ the need for $\gamma_m > 1.64$ is low. Hence, at $\gamma_m = 1.4$ the failure probability for the conditions under consideration is $1\cdot10^{-3}$.

It should be noted that failure probability Q_p in the majority of cases determines the risk of initiation of a fatigue macrocrack, which is followed by its growth to critical sizes, at which transition to a spontaneous fracture takes place. Therefore, the values of $\gamma_m = 1.0$–1.4 recommended in [4] correspond to the probability of initiation of a fatigue crack equal to $Q_p = 5\cdot10^{-2} - 1\cdot10^{-3}$, which is quite reasonable, depending on how serious the anticipated consequences might be [4].

The possibility of obtaining more reasonable qualitative characteristics concerning the probability of initiation of fatigue cracks for individual welded joints allows estimating the possibility of safe operation of individual weldments with a large number of different types of welded joints (different FAT) and different stress ranges (Table 4).

The known relationships are used in the studies:

$$Q(n) = 1 - \exp\,[-nQ(1)];$$
$$\Sigma Q_p = 1 - \exp\,[-\Sigma Q(n)]. \quad (5)$$

It can be seen from Table 4 that probability ΣQ_p is always higher than probability $Q(n)$, which in turn is higher than $Q(1)$, i.e. ensuring safety of a weldment only from one of the weakest joints by ignoring characteristics of other joints is far from being always grounded.

CONCLUSIONS

1. Fatigue fracture resistance of a welded joint is a rather stochastic value. In this connection, the IIW recommendations [4] based on statistical processing of experimental data with a guaranteed failure probability of $5\cdot10^{-2}$, combined with recommendations for safety factor $\gamma_m = 1.0$–1.4, are sufficiently well-grounded, according to the scheme of the weakest link for welded structures under high-cycle fatigue conditions.

2. Combining the experimental data generated by some institutions on probabilistic characteristics of fatigue resistance with the IIW recommendations for high-cycle fatigue of welded structures from ferritic-pearlitic (ferritic-bainitic) structural steels leads to expansion of the calculation capabilities for estimation of safety by using probabilistic approaches.

1. (1990) *Strength of welded joints at variable loads*. Ed. by V.I. Trufyakov. Kiev: Naukova Dumka.
2. Kogaev, V.P. (1977) *Strength calculation at time variable stresses*. Moscow: Mashinostroenie.
3. Maddox, S.D. *Fatigue strength of transverse one-side welded joints*. www.svarkainfo.ru
4. (1996) Recommendation for fatigue design of welded joints and components. *IIW Doc. XIII-1539–96/XV-845–96*.
5. (1987) *Design with EHS and AR plate*. Oxeloesund: Svenskt Stal Heavy Plate Division.