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RELIABILITY OF WELDED JOINTS AND STRUCTURES (SELECTED ARTICLES)--ETC(U)

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FOREIGN TECHNOLOGY DIVISION

AIR FORCE SYSTEMS COMMAND

RELIABILITY OF WELDED JOINTS AND STRUCTURES
(SELECTED ARTICLES)

FOREIGN TECHNOLOGY DIVISION

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yë or ë. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

GREEK ALPHABET

Alpha	Α	α	**α**	Nu	Ν	ν	
Beta	Β	β		Xi	Ξ	ξ	
Gamma	Γ	γ		Omicron	Ο	ο	
Delta	Δ	δ		Pi	Π	π	
Epsilon	Ε	ε	**ϵ**	Rho	Ρ	ρ	**ϱ**
Zeta	Ζ	ζ		Sigma	Σ	σ	**ς**
Eta	Η	η		Tau	Τ	τ	
Theta	Θ	θ	**ϑ**	Upsilon	Υ	υ	
Iota	Ι	ι		Phi	Φ	φ	ϕ
Kappa	Κ	ϰ κ	**ϰ**	Chi	Χ	χ	
Lambda	Λ	λ		Psi	Ψ	ψ	
Mu	Μ	μ		Omega	Ω	ω	

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this translation were extracted from the best quality copy available.

ESTIMATION OF THE RELIABILITY OF WELDED JOINTS.

Cand. of the tech. sciences V. N. Volchenko.

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Quality and the reliability of welding. To the questions, bonded with an improvement in the quality and reliability of articles, with each year is given increasing attention. This is related also to welding. As a result of welding process must be provided proper quality of the obtained welded joint. Into concept "welding", to analogously accepted in England, the USA and other countries Welding, we can include/connect entire totality of the phenomena, caused the technological chain/network: equipment is a welding process - article. Here enter other, bonded with the realization of this chain/network factors, for example the condition of welding and operation, the initial materials, equipment, etc.

By the quality of article or system it is accepted to call the totality of the properties of article, which determine its suitability for operation. Welded joint or construction in the determined stage of technological process can be considered article. Under the operation of welded joint in this case it is expedient to understand the totality of all phases of its existence, beginning from the process of welding and heat treatment, including storage, utilization in construction, repair, etc.

The quality of welded joint depends on many factors (Fig. 1). For the majority of the well weldable materials it is provided by means of the correct conduct of process by welder-operator or automatic machine with the reliable work of equipment and equipment, the high quality of the initial materials, good preparation and the assembly of joint.

The concept of the quality of welded joint depends substantially on the conditions of its utilization. If operating conditions are such, that is required the material with special not easily attainable are such, that is required the material with special not easily attainable properties, then the good-quality welded joint also turns out to be difficult to achieve. For example, high-strength steel of the type VKS have ultimate strength to 200 kg/mm² with very small plasticity. Therefore, in spite of the high quality of all stages of the execution of welding, the reliability of welded joint can be obtained low.

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To at present the metals diffucult to weld are related some alloy steels, alloys and nonmetallic materials. Especially complicatedly reliable joint of the heterogeneous materials between themselves. Requirements for quality and process of joint in all cases are different.

Up to now frequently are allow/assumed the inaccuracies in the determination of quality and reliability of articles, in their comparative quantitative evaluation for the different conditions of welding. Therefore it is expedient to utilize some basic concepts of reliability theory, accepted in radio electronics and automation and introduced recently in machine-building [2]. Let us examine some terms of reliability.

The reliability is one of the sides of the quality of article or system, by its most important generalized characteristic, divided usually into three components: reliability, service life and maintainability. Reliability is a function of time. Therefore they say that the reliability is quality, developed with time.

Reliability is property of article to remain operable, not to have failures during the determined time interval under the assigned/prescribed operating conditions. Reliability quantitatively estimated at the probability of failure-free operation, at the rate of failures, etc.

Service life is a capability for the prolonged operation of article during the necessary maintenance. Service life quantitatively estimated at technical resource/lifetime, operating time to failure or another limiting condition.

Fig. 1. Factors which influence welding quality.

Key: (1). Conditions of welding preparation, assembly and so forth. (2). Reliability of equipment. (3). Quality of the welding process. (4). Qualification and the state of welder. (5). Reliability of equipment. (6). Quality of the initial materials. (7). Quality of welded joint. (8). Properties of material. (9). Operating conditions: the load, the medium, the temperature.

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Maintainability is adaptability of article to prevention/warning, detection and the elimination of failures. It is characterized by the labor inputs, time and resources for repair work.

Failure is called the total or partial loss of the work of article.

Work is this state of the article, with which are satisfied the requirements, establish/installed to the basic parameters of article. If article does not correspond to requirements for its secondary parameters, then this state is called flaw/defect. For example, in weld the flaw/defects, which do not disturb the work of joint, are considered the separate pores, the undercuts, the small inclusions and the poor fusions within the limits of the established/installed tolerances.

Failures are divided into sudden and gradual. Deterioration failures are bonded with a gradual change in the determining parameters of article as a result of wear, aging, fatigue, creep. Deterioration failures can be foreseen (to forecast), investigating, for example, the changing parameters of welds. The random failures are random events, cannot be foreseen them, but it is possible to estimate on the basis of theory of probability.

Some concepts of reliability theory. The quantitative determination of the reliability of articles requires the knowledge of a series of the initial characteristics, determined by the methods of mathematical statistics and designed on the basis of theory of probability. They include the following:

a) the probability of the failure-free operation of articles P (t) - this is the probability of the fact that under specific conditions of operation within the limits of the mission time of work t will occur not one failure. Sometimes P (t) are called the function of reliability, since it most completely characterizes this property of articles.

Statistically the probability of failure-free operation is characterized by the ratio of number n (t) exactly working to torque/moment t of articles (systems) to the total number of articles N, which are located under observation; this relation

$$P_N(t) = \frac{n(t)}{N}$$

will be the empirical function of reliability. With an increase of N the function approaches P (t) so that $P_N(t) \approx P(t)$ (with $N \to \infty$).

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b) failure rate f (t) - this ratio of the number of failed articles Δn in time interval Δt after torque/moment t to the prime number of tested articles N:

$$f(t) = \frac{\Delta n}{\Delta t N}.$$

The failure rate actually is the probability density of random number distribution, i.e., operation time between failures T_{cp}, approaching it with an increase of the number of observations.

c) the intensity (danger) of failures λ (t) - this relation the number of failed articles Δn for time Δt after torque/moment t to the average number of exact articles n (t) to the moment of time t:

$$\lambda(t) \approx \frac{\Delta n}{\Delta t n(t)};$$

λ (t) is the local characteristic of the reliability, which determines the reliability of cell/element at each given moment of time. Numerous experimental data show that for the wide circle of articles the function λ (t) can be broken into three sections (Fig. 2). On the first of them λ (t) has increased values. This is connected with the fact that in large batch always are articles with the concealed/latent flaw/defects. These articles get out of order rapidly, and period I calls period breakings in. Period II is called the period of normal operation. It is characterized by the constant (or approximately constant) value of failure rate. Last/latter period III is a period of aging. The here irreversible physicochemical phenomena or the wear lead to deterioration in the quality of article, and λ (t) grow/rises.

Form curved λ (t), called sometimes "curved life", somewhat is changed depending on the operating mode. The floating mode/conditions P (Fig. 2) descend λ (t) and increase the service life of article.

The failure rate is the convenient characteristic of the reliability of different articles and easily is determined from experiment in the process of operation or when conducting special reliability tests.

d) the mean time of failure-free operation T_{cp} this most probable value of the operating time of article. Geometrically it is expressed by the area, limited by axes of coordinates and by the curve of P (t). T_{cp} it is the mean time between failures, and for the unrestorable articles - by operation time to the first failure. For obtaining values T_{cp} with accuracy/precision to ±10o/o quantity of observations must be not less than 10.

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The reliability of articles is estimated on the basis of experimental data the statisticians of the failures, which make it possible to judge the laws of the time allocation of failure-free operation. The basic theoretical dependences, utilized for determining the reliability of articles, are the following three laws (Table 1):

1. Exponential (exponential) law of reliability, used for the analysis of the articles, passed period the breakings in also of the working under effect mechanical and climatic loads. Most characteristic are the random failures, λ (t) = const. 2. Normal (Gauss) law of reliability, used during a gradual change in the parameters. Characteristic failures - "wear", λ (t) $\neq$ const.

3. The law of the reliability of Weibull considers the degree of the effect of the preceding operation and is valid during the study of strength and service life of mechanisms. The law of Weibull and corresponding to it characteristic failures occupy the intermediate position between two of first laws. With $\nu=1$ the law of Weibull is obtained exponentially.

The basic formulas, which describe the parameters of the laws of the distribution of reliability, are given in Table 1. In terms of greatest simplicity in conducting mathematical unpacking/facings differs exponential law. It is applied most frequently, especially during calculations to the reliability of the systems.

Methods of the estimation of the reliability of welded joints. Welded joint, being part of any article, constructions or mechanisms, undoubtedly it affects the indices of the reliability of this article. Welding can attenuate/weaken material, thereby lowering the probability of the failure-free operation of article P (t) or its service life T_{cp}.

When evaluating the reliability of the mechanisms, which have welded joints or constructions, it is necessary to know the characteristics of the reliability of the corresponding weldments (joints or constructions). Of three characteristics of reliability to evaluate weldments it is possible to utilize in the majority of cases only either reliability or service life. Maintainability is necessary usually only when evaluating the reliability of equipment and systems.

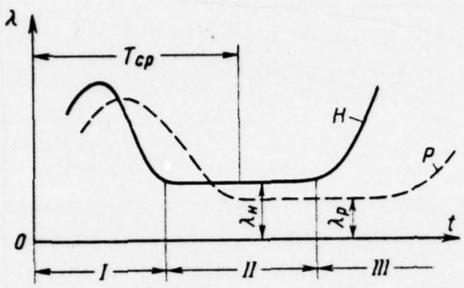

Fig. 2. Dependence of the rate of failures of articles of time λ (t) with nominal H and floating P the operating modes.

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Table 1. Basic mathematical dependences of the theory of reliability [1, 2].

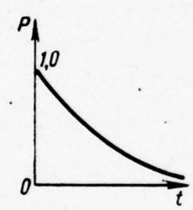
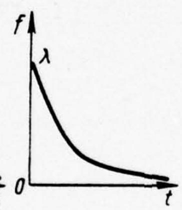
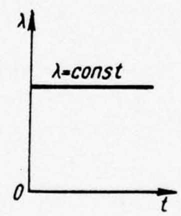
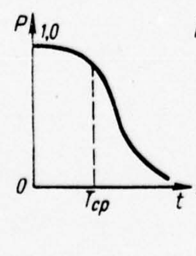
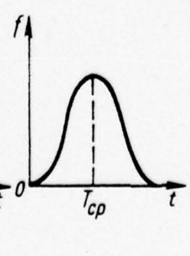
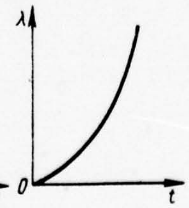
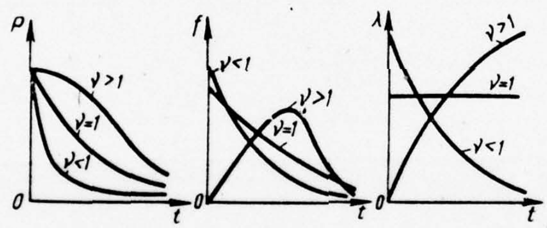
(1) Закон безотказности	(2) Вероятность безотказной работы	(3) Частота отказов	(4) Интенсивность отказов	(5) Наработка на отказ (долговечность)
—	$P(t)=\int_t^{\infty} f(t)\,dt$	$f(t)=-\frac{dP}{dt}$	$\lambda(t)=\frac{f(t)}{P(t)}$	$T_{cp}=\int_0^{\infty} P(t)\,dt$
(6) Экспоненциальный	$P(t)=e^{-\lambda t}$ 	$f(t)=\lambda e^{-\lambda t}$ 	$\lambda(t)=\lambda$ 	$T_{cp}=\frac{1}{\lambda}$
(8) Нормальный (Гаусса)	$P(t)=\frac{1}{\sqrt{2\pi}\,\sigma}\times\int_0^{\infty} e^{-\frac{(t-T_{cp})^2}{2\sigma^2}}$ 	$f(t)=\frac{1}{\sqrt{2\pi}\,\sigma}\times e^{-\frac{(t-T_{cp})}{2\sigma^2}}$ 	$\lambda(t)=\frac{1}{\sqrt{2\pi}\,\sigma}\times\frac{e^{-\frac{(t-T_{cp})^2}{2\sigma^2}}}{0{,}5-\Phi\left(\frac{t-T_{cp}}{\sigma}\right)}$ 	T_{cp} [1 и 2] (7)

Table 1 Con't.

(9) Вейбулла	$P(t) = e^{-\lambda t^{\nu}}$ при $\lambda t^{\nu} \ll 1$ $P(t) = 1 - \lambda t^{\nu}$	$f(t) = \nu\lambda \times$ $\times t^{\nu-1} e^{-\lambda t^{\nu}}$	$\lambda(t) = \nu\lambda t^{\nu-1}$	$T_{cp} =$ $= \int_0^\infty e^{-\lambda t^{\nu}} dt$



Note. σ are standard deviations (dispersion); Φ - the normalized function of Laplace; ν the parameter of the reliability of Weibull.

Key: (1). Law of reliability. (2). Probability of failure-free operation. (3). Failure rate. (4). Failure rate. (5). Mean time between failures (service life). (6). Exponential. (7). and. (8). Normal (Gauss). (9). Weibull.

Page 39. The quantitative estimation of the reliability of welded joints, according to our opinion, can be conducted by two methods (Fig. 3): a) by the directly full-scale statistical tests of the "absolute" reliability of weldments; b) by the determination of reliability with the aid of the relative quality coefficients of welded joint in comparison with the material of article.

For special tests for "absolute" reliability it is expedient to subject to weldments in such a case, when are observed the following conditions:

1. There is a need for obtaining **time/temporary** quality coefficients - reliability of weldments $P_{cB}(t)$; $\lambda_{cB}(t)$ or T_{cp}.

2. There is a possibility of conducting the statistical full-scale tests of articles under conditions and for duration, assigned/prescribed by operation (or under the equivalent to them conditions of accelerated tests).

3. The dimensions of articles allow/assume their full-scale tests.

4. Expenditures on the statistical tests of the series of articles are justified by the conditions of their work, by the mass character of the issue of articles or by their exceptional responsibility.

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During the full-scale tests of "absolute" reliability the sufficiently large number of articles N (not less than 10) is subjected to constant load under the assigned/prescribed conditions, which approach full-scale. Through small time intervals Δt are checked the determining parameters of tested articles and are reveal/detected the failed articles. The determining parameters of the quality of articles depend on the operating conditions and properties of material. They can be explained by technological or structural strength, density, corrosion resistance etc. (Fig. 4).

Depending on the danger of one disturbance/breakdown or the other of quality in the process of operation is determined the "predominant failure" of article.

The predominant (or prevailing) failure - this is the failure, which most probable under these operating conditions. As examples of failures can serve, for example, failure as a result of low technological strength, the failure or the achievement of the inadmissible amounts of strains as a result of the loss of structural strength, the disturbance/breakdown of density as a result of porosity or low corrosion resistance of weld, etc.

The number of possible failures is very great. After estimating the conditions of the predominant failure and after creating them for a tested article, it is possible to obtain statistics of failures and to quantitatively calculate reliability. The experimental intensity of the failures

$$\lambda(t) = \frac{\Delta n}{\Delta t n(t)},$$

where t is a beginning of an interval Δt; Δn - the number of articles, which failed for time Δt; n (t) - the average number of exact articles in the selected interval.

The probability of failure-free operation for a period of time t can be determined from the following expression:

$$P(t) \approx \frac{N - \sum_{i=1}^{t/\Delta t} \Delta n}{N}.$$

Depending on the form of the obtained statistics of failures λ (t) it it is possible to approximate by one either the other theoretical curved of the examined above laws reliability (Table 1) and to calculate then P (t) or T_{cp}.

For the welded joints, which work, for example, under conditions of aging, in the agressive media under load and at high temperatures, the statistician of failures λ (t) it has usually wear character. This answers the normal law of reliability or the laws of Weibull in the parameter $\nu > 1$.

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For random failures λ (t) = const reliability P (t) can be calculated exponentially.

However, the full-scale tests of the complete reliability of weldments can be completely road, they are always necessary and feasible; therefore is proposed the simpler procedure of the estimation of work according to relative quality coefficients.

The majority of welded joints enters in this or another form in welded construction, machine or another article. If there is no replacement or the reduction of welded joints due to wear, then is the common/general/total index ofwelded construction - this is the uniform strength of weld to the base metal.

Work conditions of welded joints are very diverse, and in concept "uniform strength" can enter not only strictly strength, but also other qualitative indices, for example corrosion resistance, vacuum tightness etc. The value of the reliability of welded joint affect not all the indices of the reliability of welded joint they affect not all qualitative indices, but only those, that under the assigned/prescribed conditions can lead to failure. By knowing the operating conditions of welded joint, it is possible to select the most probable combination of the possible failures or one predominant failure. Then are determined values of quality coefficients K, which show the work of welded joint in comparison with material for the conditions of the predominant failure.

Fig. 3. Estimation of the reliability of welded joints according to the full-scale statistical tests of articles and according to the quality coefficients of specimen/samples.

Key: (1). Estimation of the reliability of welded joints. (2). Full-scale statistical tests of articles bench and operational. (3). Comparative statistical tests of specimen/samples. (4). Characteristics of material. (5). Characteristics of welded joints or constructions. (6). Quality coefficients etc.

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For example, with failure probability as a result of the disturbance/breakdown of the static or vibration strength of corrosion resistance quality coefficient K we will obtain from the formulas

$$K_{стат} = \frac{\sigma'}{\sigma}; \quad K_{вибр} = \frac{\sigma'_r}{\sigma_r}; \quad K_{корр} = \frac{v_к}{v'_к};$$

where σ, σ_r the strength of material (static and vibration);

σ', σ'_r the strength of the welded joint, made by the assigned/prescribed welding method;

$v_к$, $v'_к$ the rate of the corrosion of the base material ($v_к$) and welded joint ($v'_к$).

Analogously calculate quality coefficients in the elongation per unit length or the angle of knee, impact toughness and other indices. For determining coefficients of K can be used the available in the literature results of statistical weld tests, made on different materials (Table 2).

Table 2. Some quality coefficients of welded butt joints.

(1) Металл	(2) Толщина в мм	(3) Сварка	(4) Коэффициенты качества K		
			$K_{стат} = \frac{\sigma'}{\sigma}$	$K_{вибр} = \frac{\sigma'_r}{\sigma_r}$ (5) при $r = -1$	$K_{корр} = \frac{v_к}{v'_к}$ (20% HCl)
(6) Низкоуглеродистая сталь	5—10	(7) Ручная электросварка:			
		Э-34	0,8—0,85	—	—
		Э-42	1,0—1,1	—	—
		(8) Автоматическая под флюсом	0,95—1,2	—	—
(9) Сталь 18-8	3—4	(10) Аргоно-дуговая вольфрамовым электродом	0,9—1,0	0,85	0,45—0,5
ВКС1	2—3	(11) То же	0,9—0,95	—	—
АМг6	5—10	»	0,85—0,95	—	—
ВТ1Т	2—3	(8) Автоматическая под флюсом	1,1—1,2	—	0,65—0,7
30ХГСНА	5—10	»	1,1—1,0	0,65	—
Д16Т	4—6	(10) Аргоно-дуговая вольфрамовым электродом	1,0—1,1	0,8—0,85	—

Key: (1). Metal. (2). Thickness in mm. (3). Welding. (4). Quality coefficient K. (5). with. (6). Low-carbon steel. (7). Manual electric welding. (8). Automatic in flux. (9). Steel. (10). Argon-arc by tungsten electrode. (11). The same.

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Thus, during determination of reliability of the article as a whole it is necessary to consider the relative quality of welded joints with the aid of coefficient of K, which can be determined for simpler specimen/samples and employing less complex procedure, than during the full-scale tests of reliability. If is known failure rate under these conditions for a material $\lambda_{м}$, then for weld joint $\lambda_{св}=\frac{\lambda_{м}}{K}$ (Fig. 3). If K > 1, then it is accepted as K = 1 and $\lambda_{св}=\lambda_{м}$, since reliability will be determined here by material.

The different flaw/defects of the welded joint, which exceed the tolerances, which exist for this welding method, can additionally lower the reliability of article. By knowing character and the value of flaw/defects, and also the degree of their effect on one or another index of quality (vibration and static strength, corrosion resistance etc.), it is possible to determine the relative quality of joint with the flaw/defects: $K_{деф}=\theta K$, where θ is the coefficient, which considers the effect of flaw/defect under conditions of the predominant failure and determined for the appropriate graphs.

Some ways of obtaining faultless welded joints. Obtaining high-quality welded joint is determined by a number of factors, shown in Fig. 1. If we ensure the high quality of the initial materials, then decisive are the reliability of equipment and equipment and the qualification of working-operator.

During the high qualification of welder it is possible to manage with the simplest, but highly reliable equipment. Quality control of welding in this case will be the concluding operation and it will make it possible indirectly to estimate the reliability of the obtained joint.

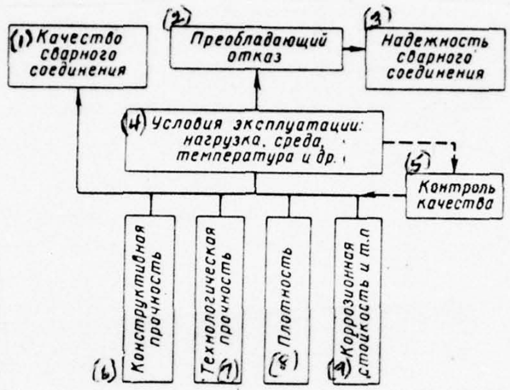

Fig. 4. Determination of the predominant failure of welded joints.

Key: (1). Quality of welded joint. (2). Predominant failure. (3). Reliability of welded joint. (4). Operating conditions: the load, the medium, temperature, etc. (5). Quality control. (6). Structural strength. (7). Technological strength. (8). Density. (9). Corrosion life, etc.

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Thus, we usually deal with preceding quality control of the initial materials and with the subsequent inspection of finished articles, whereupon control can be subjected to all articles (100o/o- control) or their part (spot check). 100o/o- the control usually completely of roads, and during spot check is certain probability that as a result of those or other reasons some articles will turn out to be all the same defects. The control in this case is passive.

Is more effectively application/use, along with the subsequent control, active quality control in the process of the welding of article.

The control of process provides for: a) maintaining within the optimum limits of all parameters of mode/conditions (programming from the parameters); b) feedback from the quality of the obtained weld to the parameters of mode/conditions (tracking in quality). In the simplest case this control of process is realize/accomplished constantly by welder itself. However, the rates of processes increase, requirements for quality are increased.

In a number of cases operator's presence is undesirable or even is impossible due to the special conditions of production (high temperature, the harmful medium and of, etc). Then all the fluctuations of the parameters of mode/conditions in the welding process, and also the technological and structural/design disturbance/perturbations of welded joint must be mastered with the aid of the control systems and (APU). The stabilizing, program and servo systems must ensure not only the execution of the joints of high quality, but because of feedback must guarantee its constancy. With these the count of feedback to guarantee its constancy. Under these conditions the subsequent control can be brought to minimum.

However, the creation of the complex welding machines, equipped with systems APU, and the expensive control are justified only in such a case, when the sum of expenditures on their development and operation is small as compared with the cost of article and fast enough is warranted, and, by determining expenditures, it is necessary to consider possibility and the consequences of the failure of welded joint.

If, for example, due to the loss of the work of the welded joint of conduit/manifold is feasible the failure of entire object, then one should consider the cost of expenditures on the elimination of the consequences of this failure. In this case the economic advisability of automation and control is determined by the relation, which can be named the economic criterion of automation and control (ek) [ЭКА]:

$$ЭКА = \frac{\text{(1) Стоимость устранения последствий отказа}}{\text{(2) Стоимость сварки и контроля}} = 10^3 \div 10^6.$$

Key: (1). Cost of the elimination of the consequences of failure. (2). Cost of welding and control.

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If the criterion of ek composes value 10^3-10^6 and more, then the automation and the careful control of welding are completely justified. This example we have during the welding of the technological conduit/manifolds of heat and power plant, which work on superhigh steam parameters by pressure to 250 at with temperature to 500-600°C. The gap of one butt with cost in several rubles leads here to the failure of entire object - boiler aggregate and building. The reduction of this failure bypasses already into thousands and millions of rubles.

Conclusions.

1. The quality of the obtained welded joints is determined in essence by four by factors: a) by the quality of the welding process, which depends on the reliability of equipment and tools; b) by the quality and the properties of the initial materials; c) by the qualification and the state of welder; d) by the conditions of

welding and operation.

2. As the generalized quality coefficient of welding, its quantitative "scan/development in time", can serve the reliability, which includes reliability and the service life of articles.

3. According to experimental data of rates of failures λ (t) welded joints either welding equipment by methods mathematical statisticians is calculated the probability of the failure-free operation of article P (t), which in the majority of cases can be described by one of the three laws: by the exponential, normal (Gauss) or distribution of Weibull.

4. Are given two procedures of the estimation of the reliability of welded joints under conditions of the so-called prevailing failure:

a) according to the results of full-scale statistical tests with determination directly $\lambda_{cв}(t)$; $P_{cв}(t)$ and T_{cp} (T_{cp} — the average life); b) with the aid of quality coefficients K, which characterize the relative quality of welded joint in comparison with material.

5. The task of the service of the reliability of welding one

should consider:

a) conducting full-scale and comparative weld tests and the statistical interpretation of the results: the development/detection of the laws, which determine the reliability of welding for different materials, processes and operating conditions; the selection of the most effective processes of welding and control;

b) the implementation of the procedure of construction and production of welding equipment with the assigned/prescribed high reliability on the basis of the analysis of statistics of failures and values of failure rates for the cell/elements of welding equipment and equipment for control.

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EFFECT OF TECHNOLOGICAL DEFECTS ON SERVICE LIFE AND RELIABILITY OF WELDED JOINTS.

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The service life and the reliability of welded constructions in operation is determined, along with other factors, the presence in them of the stress concentrators and deformations, which include the poor fusions in the middle of weld during bilateral butt welding, poor fusions radically of weld during indirect welding, the nonfusion between layers during laminated welding, nonfusions on edges, undercuts, pores, flux contaminations and the connection/inclusions of oxides, and also the defect form of weld reinforcement.

Such technological flaw/defects are encountered fairly often during the welding of constructions, and therefore the objective estimation possibly of their effect on the strength of the joint is urgent task during design and inspection of welded constructions.

Some of the enumerated flaw/defects (for example, poor fusions are natural stress concentrators and deformations) - can be used when evaluating the sensitivity of welds to notch. The degree of the danger of flaw/defects depends on the stressed state of construction, orientation of flaw/defect, character and form of loading, sensitivity of metal to stress concentration. The sensitivity of metal to stress concentration (notch) can be estimated at testing for impact bending, for elongation with slant, etc [1].

However, to evaluate the sensitivity of weld material in welded joint to welding defect (poor fusion, pores, connection/inclusions, undercuts) the enumerated methods not always can be used due to the inconstancy of the parameters of flaw/defect (form, size/dimensions).

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In the present work the sensitivity of weld in butt joint to the poor fusion and other flaw/defects, which disturb the continuity of working section/cut, is estimated coefficient of sensitivity q:

$$q = \frac{\sigma_{в.р} - \sigma_{в.д}}{\sigma_{в.р}},$$

where $\sigma_{в.р}$ -the design limit of the strength of butting flush joint of weld with the different value of flaw/defect; $\sigma_{в.д} = \frac{P_i}{F_0}$ the real tensile strength, obtained during testing butting specimen/samples without strengthening with the different value of flaw/defect (poor fusion); F_0 - the original cross-sectional area of specimen/sample.

$\sigma_{в.р}$ varies in proportion to a contraction of area of the working section/cut of specimen/sample from ultimate strength of the sample without flaw/defect to zero. With $\sigma_{в.р} \leqslant \sigma_{в.д}$ $q \leqslant 0$. This means that the weld in butt joint is insensitive to stress concentration (flaw/defect), i.e., flaw/defect in this case causes only decrease in the working section/cut. For the welds, sensitive to stress concentration, $q > 0$. The estimation of welded joints according to coefficient of q is applied only with static unidirectional tension; with vibration loads the sensitivity to stress concentration (poor fusion) is estimated at the effective coefficient of concentration β.

Poor fusion - this is the acute/sharp natural notch, which has the form of crack (Fig. 1) with radius of curvature in basis/base 0.001-0.1 mm [2]. Depending on its arrangement, character and the form of loading, metal and operating conditions, the poor fusion can have a different effect on strength and service life of welded joints. With static elongation of welded butt joints made of low-carbon steel and steel Kh18N19T the poor fusion in the weld root decreases the strength of joint proportional to decrease in the working section/cut ($q \leqslant 0$) if the limits of strength and yield of weld metal no longer are equal to limits of strength and yield of the base metal.

This conclusion is made according to the results of tensile test of flat/plane butting specimen/samples without strengthening by section/cut 10 x 20 mm with the different value of the poor fusion of the weld root made of steel Kh18N9T, welded wire Sv-Kh18N19T in the medium of argon [3] and of specimen/samples made of the low-carbon steel, welded by electrodes E42 (Fig. 2) [2].

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If the yield point σ_T' weld material more σ_T the base metal, and ultimate strength are identical, then the strength of butting flush joints with the poor fusion of the root of weld 10-15o/o of thickness of sheet with static elongation virtually it does not descend. With poor fusion 20o/o ultimate strength to 5o/o it is less (Fig. 3), than in specimen/samples without poor fusion. A considerable reduction in the ultimate strength with the elongation of butt joints with poor fusion they are observed with poor fusion $\geq$25o/o, whereupon strength descends approximately proportional to decrease in the working section/cut of specimen/sample (Fig. 3). These data are acquired in the butting specimen/samples without strengthening, welded made of steel St. 3 submerged arc weldings OSTs-45 by wire Sv.08A.

The yield point of weld metal (in Gagarin specimen/samples) with the welding technique indicated by 20o/o higher than the yield point of the base metal weld reinforcement with α = 125-145° and by height 30-35o/o of thickness of specimen/sample with the poor fusion of the weld root to 20o/o increases the strength of joint with static elongation to the strength of the base metal. With the poor fusion of the root of weld 25-50o/o of thickness of specimen/sample in butt joints with weld reinforcement the strength of the base metal is not reached (Fig. 3).

a) b)

Fig. 1. Form of poor fusion in butt joints of the low-carbon steel:
a) x70; b) x150.

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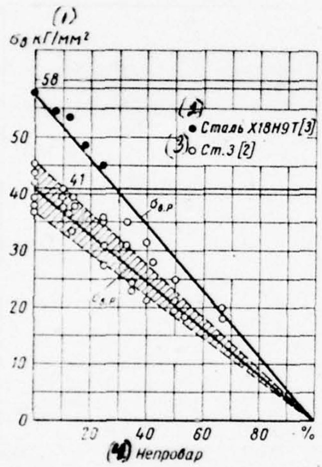
Figures 3 shows several specimen/samples, which experience/test for elongation after they hold out basis of tests ($2 \cdot 10^6$ cycles) with fatigue loading by asymmetric elongation ($r = 0.1$) without failure. After static elongation in the fracture of some specimen/samples were reveal/detected the fatigue cracks, going from poor fusion. However, static strength will not be lowered in comparison with the strength of the specimen/samples, which were not being subjected to vibration tests. This shows that the poor fusion and fatigue cracks under these test conditions have an identical effect on strength.

With the poor fusion of the root of weld $\leq$15o/o failures of specimen/samples with strengthening with elongation proceeds on the base metal, while with poor fusion $\geq$20o/o - on weld from poor fusion.

Poor fusion in the middle of butt weld (Fig. 4) has a smaller effect on the strength of the joint, than the poor fusion of root. This can be establish/installed during the comparison of the results of testing specimen/samples with the poor fusion of the root of weld (Fig. 3) with the results, obtained by Ye. K. Orlenkov (MVTU [(MBTY) - Moscow Higher Technical School) during testing flat/plane **butting** specimen/samples without strengthening with poor fusion in the middle of weld on the low-carbon steel, welded in the flux OSTs-45 by wire Sv.08A. Welding on technology indicated will make it possible to obtain weld metal with $\sigma_{в}' = 50$ kg/mm² and $\sigma_{T}' = 30$ kg/mm² with the mechanical characteristics of the base metal $\sigma_{в} = 40$ kg/mm² and $\sigma_{T} = 19$ kg/mm².



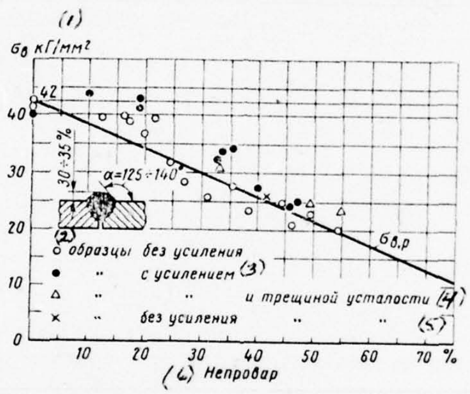


Fig. 2.

Fig. 3.

Fig. 2. Strength of butting flush joints with poor fusion radically of weld with static unidirectional tension; $\sigma_{T}' = \sigma_{T}$; $\sigma_{в}' = \sigma_{в}$

Key: (1). kg/mm². (2). Steel. (3). See. (4). Poor fusion.

Fig. 3. Strength of butt joints with poor fusion radically of weld with static unidirectional tension; $\sigma_{T}' > \sigma_{T}$; $\sigma_{в}' = \sigma_{в} = 42$ kg/mm².

Key: (1). kg/mm². (2). specimen/samples without strengthening. (3). specimen/samples with strengthening. (4). specimen/samples with strengthening and fatigue crack. (5). specimen/samples without strengthening and by fatigue crack. (6). Poor fusion.

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With poor fusion to 25o/o static strength with elongation it does not descend; with poor fusion 25-35o/o strength descends to 5-10o/o (Fig. 4). Poor fusion 45-50o/o decreases the strength with static elongation to 60-70o/o from the strength of joint without flaw/defect.

Unlike low-carbon steel, the welded joints of steel 30khGSNA and alloy of D16T [3] have q > 0. The limits of strength $\sigma_{в.д}$ butting flat/plane specimen/samples without strengthening with poor fusion 7-40o/o made of the metals (Fig. 5) considerably lower than computed values indicated $\sigma_{в.р}$; the coefficient q grow/rises with an increase in the poor fusion (Fig. 6). Ultimate strength of the butting flush joints, which do not have flaw/defects, made of steel 30khGSNA $\sigma_в' = 75 \div 115$ kg/mm², but the alloy D16T $\sigma_в' = 22 \div 32$ kg/mm², i.e., in both cases to 30-50o/o is less than the limit of the strength of the base metal.

The analysis of the obtained results makes it possible to formulate the following conclusion: the sensitivity of welded joints to concentrator (poor fusion) with static loads is explained by the relationship/ratio between the strength characteristics (σ_B and σ_T) of the base and of weld metal. If σ'_B and σ'_T weld metal is less σ_B and σ_T the base metal, then such joint turns out to be sensitive to poor fusion ($q > 0$), i.e., their strength descends more sharply than is decreased the working section/cut of specimen/sample. With σ'_B and σ'_T weld metal, large or equal to σ_B and σ_T the base metal ($q \leqslant 0$), the welded joints are insensitive to poor fusion.

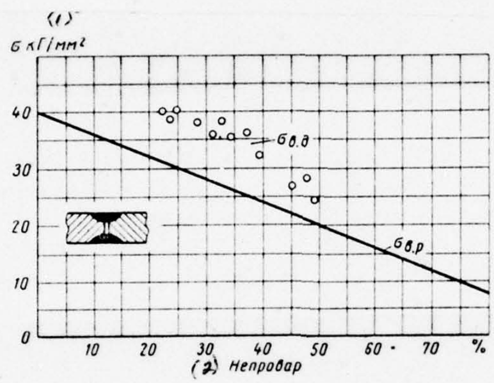

Fig. 4. Strength with the static elongation of butting flush joints with poor fusion in the middle of weld; automatic welding, flux OSTs-45 (Ye. K. Orlenkov); $\sigma_в = 40$ kg/mm²; $\sigma_T = 19$ kg/mm²; $\sigma'_в = 50$ kg/mm²; $\sigma'_T > \sigma_T$

Key: (1). kg/mm². (2). Poor fusion.

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If $\sigma'_в$ and σ'_T the melted on and base metal are equal, then strength with an increase in the poor fusion will descend proportional to decrease in the working section/cut (Fig. 2); if σ_B' and σ_T' weld metal the more appropriate characteristics of the base metal, then the strength with small poor fusions it does not descend, but with an increase in the poor fusion more than 20o/o, strength descends approximately proportional to decrease in the working section/cut (Fig. 3).

In the joints, which have q > 0 with $\sigma_B'<\sigma_B$ and q < 0 with $\sigma_B'=\sigma_B$, but $\sigma_T'>\sigma_T$, the strength of butt joints with poor fusion 15-20o/o with static loads can be raised because of smooth weld reinforcement. In the joints, insensitive to poor fusion with $\sigma_B'>\sigma_B$, an increase in strength of joint with poor fusion to 20o/o of thickness of sheet because of weld reinforcement is inexpedient, since the strength of weld metal is higher than the strength of the base metal. With poor fusion radically of weld more than 20o/o weld reinforcement in all cases does not increase the strength of joint with poor fusion to the strength of the base metal (Fig. 3), even if the height of weld reinforcement is equal to the value of poor fusion or more than it, since with an increase in poor fusion and weld reinforcement is increased the eccentricity of the application of axial load.

In butt joints the poor fusion substantially lowers the deformability of joints with static loads.

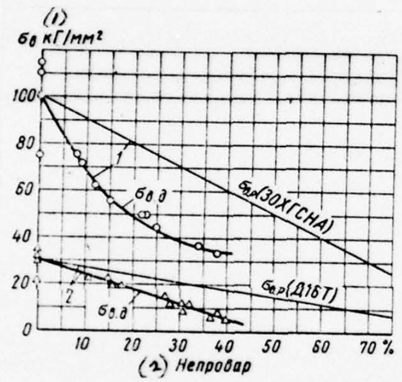

Fig. 5.

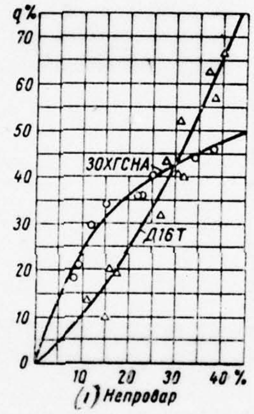

Fig. 6.

Fig. 5. Strength with the static elongation of butting flush joints depending on the value of poor fusion [3]: 1 - steel 30KhGSNA, $\sigma_{в}=150\div170$ kg/mm², flux AN-3, wire 18KhMA; 2 - alloy D16T, $\sigma_{в}=42\div44$ kg/mm², welding in argon by wire AK.

Key: (1). kg/mm². (2). Poor fusion.

Fig. 6. Sensitivity (qo/o) of butt joints to poor fusion radically of

weld with static elongation.

Key: (1). Poor fusion.

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The stress-strain diagram of butting specimen/samples made of low-carbon steel they show that already with poor fusion 11-22o/o elongation per unit length on base 70 mm descends 2 times in comparison with the elongation per unit length of specimen/sample without strengthening and without the flaw/defect, which failed on the base metal, since $\sigma_T < \sigma_T'$. With an increase of the poor fusion from 30 to 50o/o deformability sharply it falls (Fig. 7).

The strain distribution during elongation according to the working length of specimen/samples without strengthening with the different value of the poor fusion of the weld root, obtained on different bases (70 - 0.5 mm), is given in Table 1.

The degree of irregularity of the deformation of specimen/sample along the length can be characterized by the ratio of the absolute deformations of the individual sections of specimen/sample on different bases to absolute deformation on the base of an entire working length of specimen/sample (70 mm). This is especially convenient to evaluate the deformability of weld material in joint.

With poor fusion more than 20o/o base metal virtually is not strained and entire/all deformation of specimen/sample occurs because of weld ($\Delta l_{15}/\Delta l_{70}$ = 72-80o/o; see Table 1).

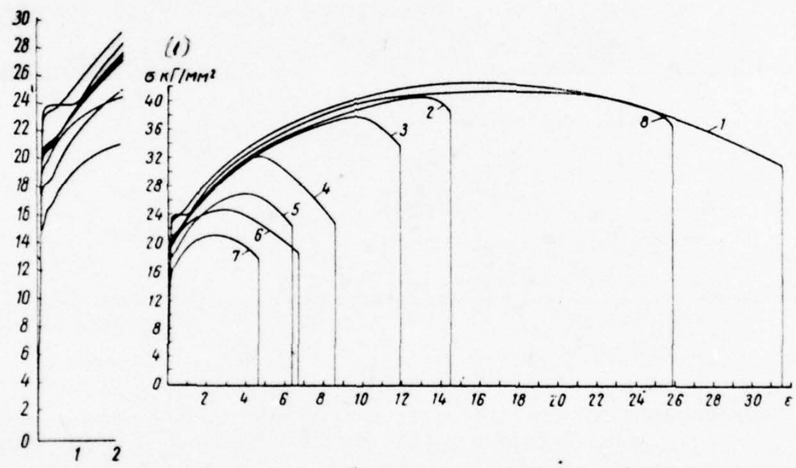

Fig. 7. Failure diagrams with the elongation of butt joints with the poor fusion of the weld root made of low-carbon steel (flux OSTs-45, wire ~~candles~~SV-08A; $\sigma_в$=42 kg/mm²; $\sigma'_в$=49 kg/mm²; σ'_T=28 kg/mm²; σ_T=24 kg/mm²): 1 - the base metal; 2 - poor fusion 15-22o/o with strengthening; 3 - the same, without strengthening; 4 - poor fusion 27-38o/o with strengthening; 5 - the same, without strengthening; 6 - poor fusion 43-48o/o with strengthening; 7 - the same, without strengthening; 8 - flush weld and without flaw/defects.

Key: (1) Kg/mm².

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Local elongations on the base of grid 0.5 mm in the presence of concentrator descend almost 3 times with respect to the strains of the base metal, the value of elongation per unit length on the base of grid barely depending on the depth of poor fusion, and it depends mainly on its sharpness. Thus, for instance, the elongation per unit length of the base metal $\varepsilon_{0,5}=130\%$, and melted on in specimen/samples with poor fusion 11-48o/o deep $\varepsilon_{0,5}=53\div44\%$ respectively (Table 1). With decrease in the sharpness of concentrator the amount of local plastic deformations is increased. In plate made of low-carbon steel with round hole 4.5 mm in radius the maximum elongation per unit length in the zone of hole on base 0.5 mm the maximum elongation per unit length in the zone of hole on base 0.5 mm composes 200o/o, with elliptical hole with the notch whose radius 0.5 mm, $\varepsilon_{0,5}=150\%$. With poor fusion in the middle of weld with radius in the basis/base of poor fusion 0.01-0.1 mm the maximum elongation per unit length is equal to $\varepsilon_{0,5}=85\div90\%$ (Ye. K. Orlenkov), while with the poor fusion of the root of weld $\varepsilon_{0,5}=40\div60\%$

[2], which will agree with data by Table 1 for a relative deformation on base 0.5 mm ($\varepsilon_{0,5}=53\div44\%$).

With alternating loads the effect of poor fusion on the strength (service life) of welded joints is developed to larger degree than with static.

Table 1. Distribution of the maximum deformations. St. 3, flux OSTs-45, wire Sv.08A, the width of weld 15-18 mm.

(1) Непровар	(2) Удлинение на базах										(3) Степень неравномерности деформации в %			(4) Место разрушения
	l_0=70 мм		l_0=50 мм		l_0=25 мм		l_0=15 мм		l_0=0.5 мм					
	Δl_{70} в мм	ε_{70} в %	Δl_{50} в мм	ε_{50} в %	Δl_{25} в мм	ε_{25} в %	Δl_{15} в мм	ε_{15} в %	$\Delta l_{0,5}$ в мм	$\varepsilon_{0,5}$ в %	$\frac{\Delta l_{50}}{\Delta l_{70}}$	$\frac{\Delta l_{25}}{\Delta l_{70}}$	$\frac{\Delta l_{15}}{\Delta l_{70}}$	
(5) Основной металл	28,1	31	18,0	36	12,9	51,6	10,3	67	0,65	130	86	59	48	—
0%	15,6	22	14,9	22,5	10,5	43	8,9	60	0,56*	112*	96	68	57	(6) По основному металлу
11—22%	8,4	12	6,3	12,6	4,4	17,6	3,9	26	0,26	56	75	52	47	(7) По шву от непровара
32—38%	3,9	5,6	3,5	7,0	2,9	11,6	2,8	18,7	0,20	41	90	75	72	(8) То же
43—48%	3,1	4,4	3,1	6,2	2,7	10,8	2,5	16,7	0,22	44	100	87	80	»

* Данные получены на образцах с ослабленным сечением (разрушение по шву).

Key: (1). Poor fusion. (2). Elongation on bases. (3). Degree of nonuniformity of deformation in o/o. (4). Position of fracture. (5). Base metal. (6). On the base metal. (7). On weld from poor fusion. (8). The same.

FOOTNOTE [1]. Data are acquired in specimen/samples with the weakened section/cut (failure on weld). ENDFOOTNOTE.

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Some plastic metals, insensitive to stress concentration with static loads, with vibration loads become more sensitive, the high-strength steel; for example, steel Kh18N9T, welded butt joints of which with the poor fusion of the root of weld 8-25o/o with axial alternating/variable elongation have a endurance limit on base N = $5 \cdot 10^6$ cycles, 4-5 times lower than the endurance limit of flush joints and without flaw/defect from the base metal. Of welded butt joints made of steel 30KhGSNA (submerged arc welding AN-3 by the wire 18KhMA) under analogous conditions the vibration strength descends only 1.8-2 times in comparison with the vibration strength of joint without flaw/defect and 2.5-3 times in comparison with the vibration strength of the base metal.

It is of interest to compare the welded joints of low-carbon steel with the joints of steels Kh18N9T and 30KhGSNA. For this purpose butting specimen/samples by section/cut 10 x 20 mm made of low-carbon steel ($\sigma_в = 42$ kg/mm²) without weld reinforcement with the poor fusion of root 17-50o/o experience/test with the asymmetric stretching vibration loads (r = 0.1) on base $2 \cdot 10^6$ cycles (submerged arc welding of OSTs-45 by wire Sv.08A). The endurance limit of specimen/samples will be lowered (Fig. 8) in comparison with joints without defects 4-10 times respectively (from 22-24 to 6 - 2 kg/mm²).

In work [3] the testing for fatigue is manufactured by constant minimum stress of cycle $\sigma_{min}=2,5$ kg/mm², which leads to an increase in the characteristic of cycle r during a reduction in the maximum stresses in the process of testing, i.e., to an increase in the coefficient of asymmetry of the cycle of loading. Increase in the coefficient of asymmetry of the cycle of loading. An increase in the coefficient of asymmetry, in accordance with the diagram of limiting cycles, leads to an increase in the endurance limit. The endurance limit of butt joints of steel Kh18N9T without strengthening with poor fusion 8-25o/o is obtained by the author [3] with the characteristic of cycles r = 0.42-0.5; during the weld test of low-carbon steel the characteristic of cycle in all cases remains constant, r = 0.1.

Thus, the sensitivity of the welded joints of steel Kh18N9T and low-carbon steel to the poor fusion of the weld root with alternating/variable elongation is virtually identical (with poor fusions to 35o/o) and higher than the sensitivity of the welded joints of steel 30KhGSNA (Fig. 9).

Figure 9 values of endurance limits gives on base $2 \cdot 10^6$ cycles for all metals indicated, including for the aluminum alloy D16T, which, as steel 30KhGSNA, is sensitive to stress concentration with static loads (Fig. 5 and 6).

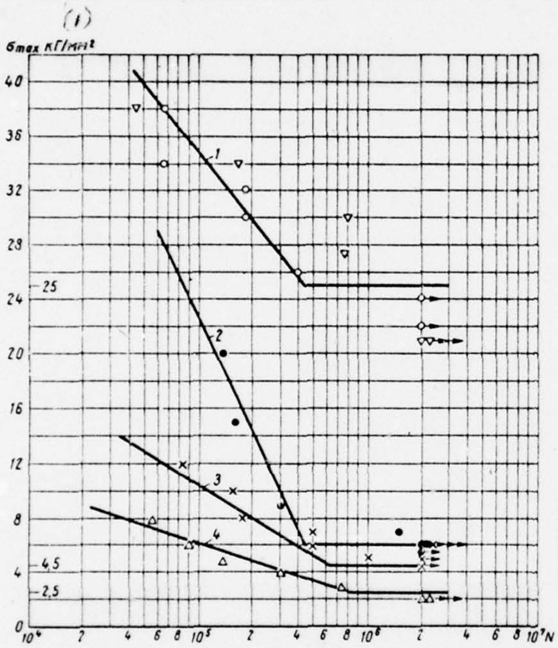

Fig. 8

Fig. 9

Fig. 8. Durability of butting flush joints with poor fusion radically of weld with the asymmetric tension: 1 - the base metal and flush weld and without flaw/defects; 2 - poor fusion 17-20o/o; 3 - poor

fusion 26-31o/o; 4 - poor fusion 44-49o/o.

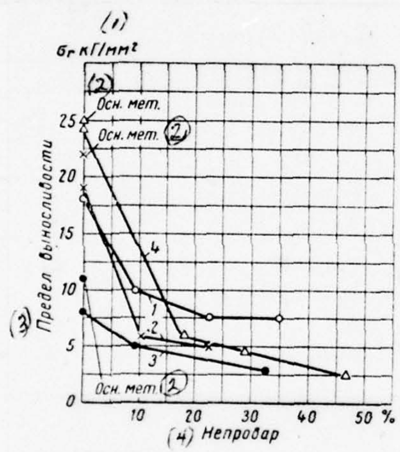

Fig. 9. Effect of poor fusion radically of weld on the endurance limit of welded butting flush joints: 1 - steel 30KhGSNA, flux AN-3, wire 18KhMA, r = 0.2-0.3; 2 - steel Kh18N9T, argon, wire Kh18N9T, r = 0.2-0.5; 3 - alloy D16T argon, wire AK, r = 0.3-0.8; 4 - low-carbon steel, flux OSTs-45, wire Sv-08A, r = 0.1.

Key: (1). kg/mm². (2). Based metal. (3). Apparitor of durability. (4). Poor fusion.

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The comparison of sensitivity to the poor fusion of the weld root according to the effective coefficient of the concentration of welded butt joints of different metals is given in Table 2. The relative sensitivity of welded joints to the poor fusion of root of steel 30KhGSNA and alloy D16T is less than the welded joints of low-carbon steel and steel Kh18N9T. However, when evaluating material one should consider data given in Table 3, which show that the metals, insensitive to stress concentration with static loads (St. 3, Kh18N9T), have relatively high endurance limit in comparison with the metals, sensitive to stress concentration with static loads (30KhGSNA, D16T).

Table 2. The effective stress concentration factors $\left(\frac{\sigma_{min}}{\sigma_{max}}\right.$ see Fig. 9) β = (σ_r of the basic metal)/(σ_r specimen/sample with flaw/defect) o/o.

(1) Металл	(2) Метод сварки	0%	10%	17—22%	27—35%	50%
(3) Низкоуглеродистая сталь	(4) Флюс ОСЦ-45; проволока Св-08А . . .	1	—	4	4,5	10
(5) Сталь Х18Н9Т	(6) Автоматическая сварка в среде аргона; проволока Св-Х18Н9Т .	1,22	3,7	4,4	—	—
(5) Сталь 30ХГСНА	(7) Автоматическая сварка; флюс АН-3, проволока Св-18ХМА	1,4	2,5	3,3	3,3	—
(8) Алюминиевый сплав Д16Т	(9) Автоматическая сварка в среде аргона; проволока Св-АК	1,4	2,2	—	3,7	

Key: (1). Metal. (2). Welding method. (3). Low-carbon steel. (4). Flux OSts-45; wire ~~candles~~ Sv-08A. (5). Steel. (6). Automatic welding in the medium of argon; the wire Sv-Kh18N9T. (7). Automatic welding; flux AN-3, the wire Sv-18KhMA. (8). Aluminum alloy D16T. (9). Automatic welding in the medium of argon; wire ~~candles~~ Sv-ak.

Table 3. Ultimate strengths of the base metal.

(1) Металл	(2) $\sigma_в$ в кГ/мм²	(2) σ_r в кГ/мм²	$\frac{\sigma_в}{\sigma_r}$
(3) Низкоуглеродистая сталь	42	25	1,7
Х18Н9Т	56	20	2,8
30ХГСНА	140	25	5,5
Д16Т	43	10	4,3

Note. Specimen/samples by section/cut 10 x 20 mm experience/test with elongation on base $2 \cdot 10^6$ cycles with the characteristic of cycle r = 0.1-0.2.

Key: (1). Metal. (2). in kg/mm². (3). Low-carbon steel.

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To the sensitivity of welded joints to stress concentrators with vibration loads an essential effect has the orientation of concentrator (flaw/defect) in the section/cut of weld with respect to the acting loads and the form of loading. With poor fusion in the middle of weld 20o/o of thickness of specimen/sample the limit of the fatigue (durability) of butt joints of low-carbon steel with the **elongation** $\tilde{\sigma}_{0,1}=12$ kg/mm^2 and with poor penetration of the root $\sigma_{0,1}$ = 6 kg/mm² (Fig. 10). The same relationship/ratio of the endurance limits of butt joints with poor fusion in middle and radically of weld is obtained on low-carbon steel for other values of poor fusion (Fig. 11). Slight difference in the characteristics of cycles (r = 0.1-0.2), with which was conducted testing specimen/samples (Fig. 11a), must not significantly change these relationship/ratios.

With symmetrical bending the poor fusion in the middle of weld to 25o/o fatigue strength does not lower; with poor fusion 40o/o endurance limit descends to 8o/o, with poor fusion 50o/o - to 30o/o. With the same values of the poor fusion, arrange/located radically of weld, the limit of the fatigue of butt joints with bending descends 2-2.5 times (Fig. 11b).

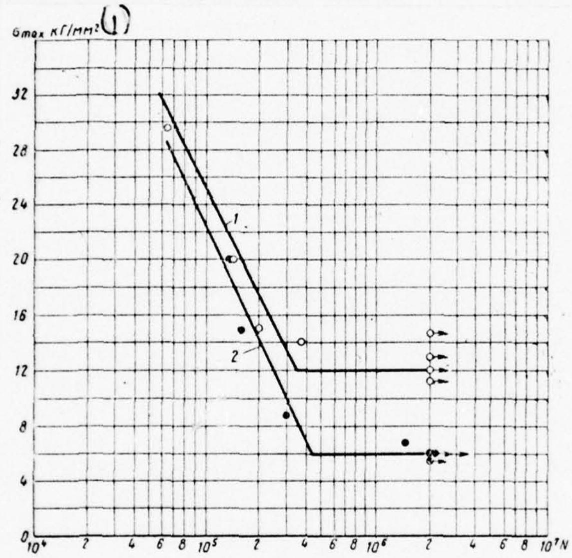

Fig. 10. Effect of the position of poor fusion in the cross section of weld on the durability of welded butt joints with poor fusion 20o/o: 1 - poor fusion in the middle of weld; 2 - poor fusion

radically of weld.

Key: (1). kg/mm^2.

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Thus, by estimating the sensitivity of welded joints to concentrators (poor fusions), it is necessary to consider the orientation of poor fusion in weld and the character of loading.

When evaluating the effect of the reinforcement of weld in butt joints with static loads it was shown, that the weld reinforcement in the welded joints, sensitive to stress concentration, with certain determined value of poor fusion increases the strength of joint to the strength of the base metal.

With vibration loads the reinforcement of weld lowers fatigue strength of butt joints without flaw/defect [4, 5]. In this case the degree of a reduction in the fatigue limit depends on the height of weld reinforcement (Fig. 12). A change in altitude of reinforcement of weld is bonded with a change in the radius of transition from the base metal to that which was melted on and the angle of coupling α weld metal a by basic (see Fig. 3). With an increase in altitude of weld reinforcement is decreased the angle α and, therefore, increases stress concentration. Usually in welded butt joints weld reinforcement is 15-30o/o of thickness of the sheets to be welded. In this case the effective coefficients of concentration β, calculated with respect to joints without flaw/defects and without strengthening, will have values, given in Table 4.

Weld reinforcement has an identical effect on vibration tensile strength of butt joints without flaw/defects made of low-carbon steel and steels 30KhGSNA (without heat aftertreatment), β = 1.6-1.7. With symmetrical bending the sensitivity is somewhat above (β = 2). With decrease in the thickness of the combinable sheets the effect of weld reinforcement is developed to a lesser degree (β = 1.4-1.5).

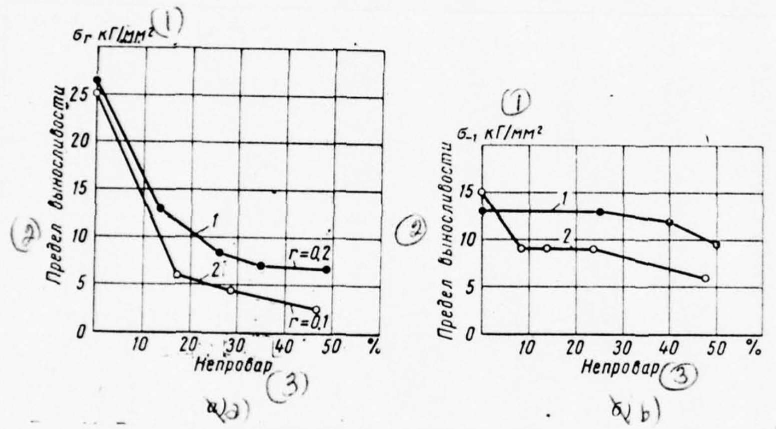

Fig. 11. Effect of position and value cf pccr fusion in the crcss sections of weld on the endurance limit of welded butt joints at asymmetric elongation (a) and symmetrical bending (b): 1 - poor fusion in the middle of weld; 2 - poor fusion radically of weld.

Key: (1). kg/mm². (2). Endurance limit. (3). Pocr fusion.

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Table 4.

Металл	Метод сварки	Условия испытания	Предел выносливости стыковых соединений с полным проваром в $кГ/мм^2$		Эффективный коэффициент β	Источник
			без усиления	с усилением		
30ХГСНА	Флюс АН-3; проволока 18ХМА	Растяжение $r = 0,2$, 10×40 мм	18	10,3	1,74	[3]
Низкоуглеродистая сталь	—	Растяжение $r = 0$, толщина 10 мм	22	13—14	1,7—1,6	[5,4]
То же	Флюс ОСЦ-45; проволока Св. 08А	Растяжение $r = 0,1$, сечение образца 10×20 мм	25	14,5	1,72	Авторы
Сталь ЭИ659	Флюс АН-348А; проволока 20ХМА	Растяжение $r = 0$, сечение образца 2×3,5 мм	30	20—22	1,5—1,4	[6]
Сталь ЭИ659	Ручная сварка УОНИ-13/85	Изгиб $r = -1$, сечение образца 10×40 мм	28	14,4	2,0	[6]

Key: (1). Metal. (2). Welding method. (3). Test conditions. (4). Endurance limit of butt joints with good penetration in kg/mm^2. (5). without reinforcement. (6). with strengthening. (7). Effective coefficient. β (8). Source. (9). Flux AN-3; wire. (10). Elongation. (11). Low-carbon steel. (12). thickness. (13). The same. (14). Flux OSTs-45; wire candles, Sv08A; (15). the section/cut of specimen/sample. (16). The authors. (17). Steel. (18). Manual welding. (19). Bending.

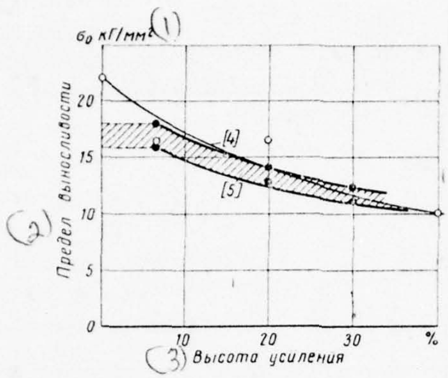

Fig. 12. Altitude effect of weld reinforcement on the endurance limit of butt joints: steel low-carbon; submerged arc welding N = 2•10⁶ cycles; r = 0.1; elongation; the thickness of metal 10 mm.

Key: (1). kg/mm². (2). Endurance limit. (3). Height of strengthening.

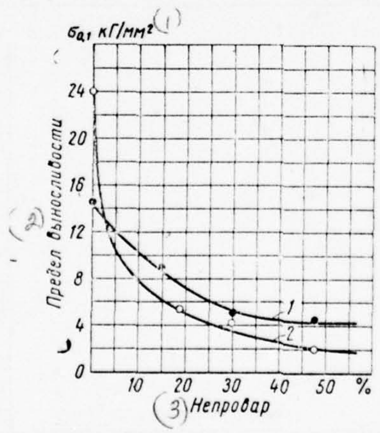

Fig. 13. Effect of the depth of the poor fusion of the weld root on the fatigue limit of butt joints with asymmetric elongation (N = 2•10⁶, r = 0.1); 1 - with strengthening 30o/o; 2 - without strengthening.

Key: (1). kg/mm². (2). Endurance limit. (3). Poor fusion.

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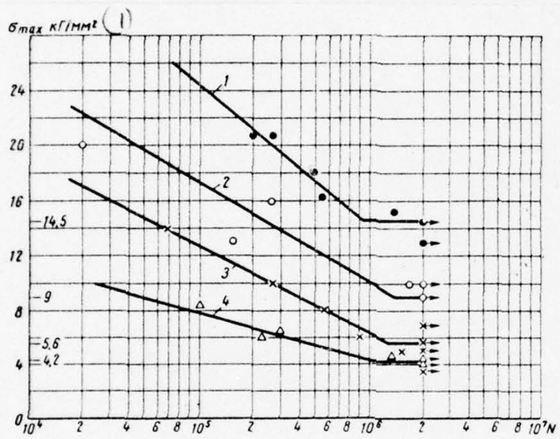

Fig. 14. Durability of butt joints with poor fusion radically of weld and with strengthening by height 30o/o with asymmetric elongation (r = 0.1; N = 2•10⁶ cycles): 1 - weld without flaw/defects; 2 - poor fusion 13-20o/o; 3 - poor fusion 30o/o; 4 - poor fusion 42-48o/o.

Key: (1). kg/mm².

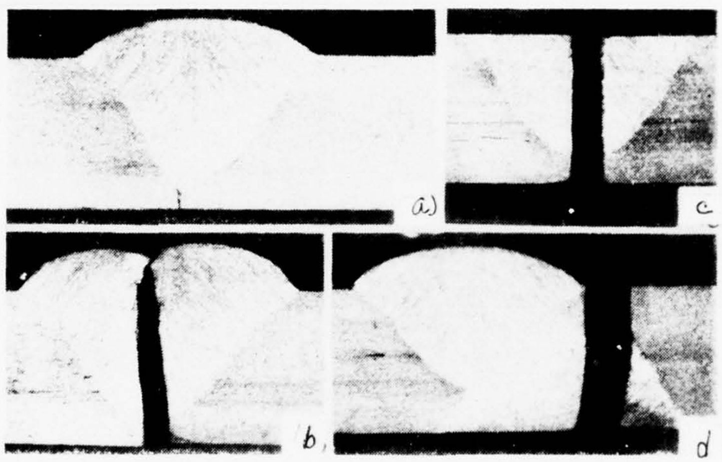

Fig. 15 character of the fatigue failures of butt joints of low-carbon steel with concentrators with the asymmetric elongation: a) butting reinforced seam and poor fusion before testing; b) the same after fatigue failure; c) butt weld with poor fusion without strengthening; d) butt weld without flaw/defects with strengthening.

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In butt joints with poor fusion, the weld reinforcement somewhat increases vibration strength, but is insignificant, that it is possible to see in Fig. 13, where are given the results of fatigue test of butt joints with strengthening (Fig. 14), also, without strengthening (Fig. 8) on low-carbon steel with the poor fusion of the weld root with asymmetric elongation. With poor fusion to 15o/o in low-carbon steel (Fig. 13) the weld reinforcement increases the durability of butt joints with elongation by 20o/o. The same increase in the endurance limit (fatigue) with poor fusion 20-25o/o [3] occurred in butt joints of steel 30KhGSNA and Kh18N9T (from 7 to 8.5 and from 3.5 to 5 kg/mm^2 respectively). In all cases when stress concentrators are present, (strengthening, poor fusion) the failure of butt joints with vibration loads began from concentrator (Fig. 15).

Conclusions.

1. The sensitivity of welded butt joints to poor fusion with

static loads with unidirectional tension depends on the ratio of the strengths of the base and of weld metal and can be estimated by the coefficient of sensitivity q.

2. In welded joints made of steel St. 3 at static loading and the positive temperature the poor fusion in the middle of weld to 20o/o and the poor fusion of the weld root to 15o/o does not lower the bearing capacity of butt joints, the weld reinforcement with the poor fusion of root more than 25o/o not increasing the strength of compound to the strength of the base metal.

3. Poor fusion sharply lowers the deformability of butt weld; in this case the amount of the maximum local plastic deformations in the place of rupture is decreased 2-3 times as compared with weld without flaw/defect and barely depends on the value of poor fusion.

4. With vibration loads the weld reinforcement for all metals is the stress concentrator, which lowers the durability (fatigue strength) of butt joints without flaw/defects, but in the presence of poor fusion the durability of compound will be determined by poor fusion, whereupon poor fusion radically is more dangerous than in the center of weld.

5. The sensitivity of welded butt joints of steels Kh18N9T and

RELIABILITY OF WELDED CONSTRUCTIONS IN WORK IN CORROSIVE ENVIRONMENTS.

Cand. of tech. sci. O. I. Steklov.

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The basic factors, which determine real strength and the work of welded constructions are metal, technology of manufacture, structural/design form, the stressed state in construction and the effect of working environment. Environments can exert corrosion, chemical, adsorptive, radiation, cavitation, erosive and other forms of effect on the metal of construction [1]. During reaction with metal, the working environment can produce reversible and irreversible) for example, with corrosion corrosion) the changes in metal, which determine the efficiency of design.

The corrosion-active media (gases, different atmospheric conditions, water, the aqueous solutions acids, alkalies, salts, the fusion/melts of salts etc.) cause the chemical either electrochemical of st. 3 to the poor fusion of the weld root with the vibration tensions is approximately identical.

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corrosion, which lowers plasticity, the strength and fatigue limit, or corrosion cracking, i.e., failure as a result of the combined action of stresses and corrosive environment.

The welded joints, working in the corrosion-active media, potentially the weak place of construction. This is caused by the larger thermodynamic instability of welded joint in comparison with the base metal.

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As a rule,

$$\Pi_{o.м} \geqslant \Pi_{c.c}; \quad \Pi^{к}_{o.м} > \Pi^{к}_{c.c};$$

$$\frac{\Pi_{c.c}}{\Pi_{o.м}} > \frac{\Pi^{к}_{c.c}}{\Pi^{к}_{o.м}},$$

where $\Pi_{o.м}$, $\Pi_{c.c}$ - the bearing capacity of the base metal and welded joint without the effect of corrosive environment; $\Pi^{к}_{o.м}$, $\Pi^{к}_{c.c}$ - is a bearing capacity of the base metal and welded joint under the influence of corrosive environment.

The properties of welded joint as compared with the properties of the base metal under conditions of corrosion are lower than under normal conditions.

For an increase in work and reliability of welded constructions in corrosive environments it is necessary to solve a series of the complex problems, most important of which:

1) research on mechanism and special feature/peculiarity of the corrosion of welded joints;

2) the development of the effective procedures of the study of the corrosion properties of welded joints;

3) the study of the corrosion properties of the welded joints of the determined alloys in connection with the specific conditions of the work of constructions;

4) the development of the methods of an increase in corrosion resistance of welded joints and work of welded constructions in corrosive environments.

Let us examine the special feature/peculiarities of the electrochemical corrosion of welded joints and their stability to alloys electrochemical potentials are different.

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Is distinguished the macroelectrochemical heterogeneity (for example, the corrosion of the hull of ship on water line, caused by a difference in the ambient conditions), which leads to the formation of macrocorrosion cell/elements; the microelectrochemical heterogeneity (e.g., the discontinuity of metal, the presence of grain boundaries, pores in protective film, stress concentration), which leads to the formation of microcorrosion cell/elements. On the surface of metal there can be the even fine/thinner, more submicroscopic electrochemical heterogeneity, bonded with the unhomogeneity of surface within the limits of groups and even separate atoms.

With the electrochemical unhomogeneity of metal on its surface appear anode and cathode sections. Those sections of metal, which have more negative electrode potential, form the anodes; sections with more positive electrode potential are cathodes. The corrosion-aggressive medium dissolves all the available for it anode sections of the surface of metal. The process of electrochemical corrosion occurs according to the following diagram (Fig. 1).

corrosion cracking, and also the methods of an increase in corrosion resistance.

Mechanism of electrochemical corrosion. [2, 3]. The corrosion instability is determined themes that in the liquid or the gaseous phase the metallic state is thermodynamically unstable; therefore the majority of metals attempts to change from metallic for ionic state. By the mechanism of the course of corrosion processes is distinguished the corrosion of two types: chemical and electrochemical.

Chemical corrosion is *subordinated* to the fundamental laws of the chemical kinetics of heterogeneous reactions and is not accompanied by the emergence of electric current (for example, corrosion in nonelectrolytes or dry gases). Electrochemical corrosion obeys the law of electrochemical kinetics and usually is accompanied by the appearance of an electric current (for example, the corrosion of metals in electrolytes). During electrochemical corrosion the first criterion of corrosion resistance of metal is the standard electrode potential, which appears during the insertion of metal into electrolyte. The lesser the potential, the lesser corrosion resistance, other conditions being equal, possesses metal.

For the different sections of the corrosive surface of real

1. Anodic process, the transition of metal ions to solution and their hydration

$$Me + mH_2O \rightarrow Me^{n+} \cdot mH_2O + ne.$$

2. Cathode process, the assimilation of electrons by any containing in solution depolarizer (D), i.e., by atom or the ion, capable of being restored (to absorb electrons) on cathode,

$$ne + D^{n+} \rightarrow D.$$

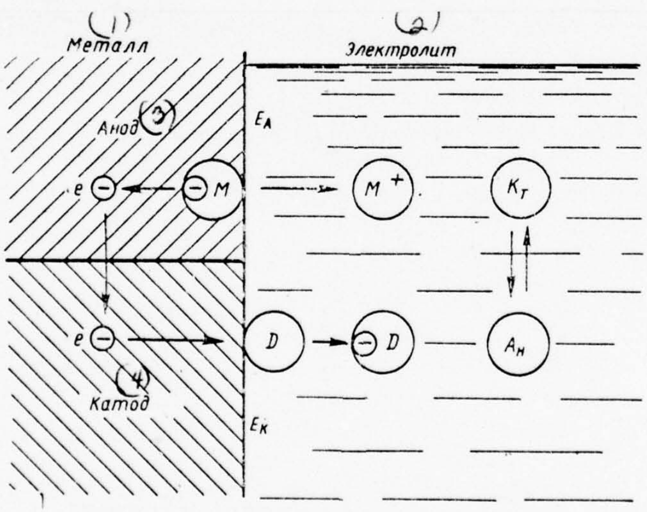

Fig. 1. Principle diagram of the electrochemical corrosion: M are metal ions; D - depolarizer; e - electrons; E_A - potential on the anode; E_K is potential on cathode.

Key: (1). Metal. (2). Electrolyte. (3). Anode. (4). Cathode.

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The most important cathode depolarizing reactions:

a) cathode process with hydrogen depolarization is a cathode reaction of the reduction of hydrogen ion into the gaseous hydrogen

$$H^{+}\cdot H_2O + e \rightarrow {}^{1}/_{2}H_2 + H_2O;$$

b) cathode process with oxygen depolarization - the cathode reaction of the reduction of oxygen with its transformation into the ions of hydroxide

$$O_2 + 2H_2O + 4e \rightarrow 4OH^{-}.$$

3. Overflowing of electricity. Course of the current between the anodes and the cathodes in metal - by electron motion from anode sections to cathode (corrosion current) and in solution - by the motion of cations from anode sections to cathode and by the motion of anions from cathode sections to anode. Failure with this mechanism will occur predominantly on the anode; on the cathode sections, where proceeds the process of depolarization, the perceptible losses of metal will not be.

Special feature/peculiarities of the electrochemical corrosion of welded joints. Uneven heating metal during welding leads to geometric, chemical, structural, mechanical unhcmogeneity and the unhomogeneity of the stressed state in the different zones of welded joint. Therefore for welded joint is characteristic the electrochemical heterogeneity cf all fcrms: macro-, micro- and submicroscopic.

Macroelectrochemical unhomogeneity is caused by a potential difference in the different zones of welded jcint, and welded joint can be considered as combination of multielectrode cell/element with the macroelectrodes: weld, the zone of superheating, recrystallization zone, the base metal.

Along with macrocells within the limits of each zone of welded joint act many local micro- and submicrogalvanic corrosion cell/elements. The rate of work of these cell/elements in the different zones of welded jcint can be different.

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Macrogalvanic corrosion cell/elements weld - the base metal for the different establish/installed electrochemical potentials it is possible to divide into three groups:

1) $E_{шва} \approx E_{осн.мет}$; the potentials of weld and base metal are virtually identical; in this case the galvanic cell does not function and the corrosion processes during welded joint are determined by the work of microgalvanic cell/elements; the difference in the rate of the corrosion of each zone of welded joint is determined by the difference in the rate of work of microcorrosion pairs in each zone;

2) $E_{шва} < E_{осн.мет}$; the metal potential of weld is more negative than of the base metal; therefore weld corrodes more intensely as a result of anodic dissolution;

3) $E_{шва} > E_{осн.мет}$; the metal potential of weld more positive, than the base metal. In this case more powerfully fails itself the base metal.

The total corrosion effect is determined by the intensity of simultaneous work macro- and microgalvanic corrosion pairs. Depending on the degree of the unhomogeneity of welded joint for the structure, the chemical composition, etc and corrosion conditions will predominate one or another mechanism of corrosion.

Figure 2 shows communication/connection between the thermal welding cycle and the properties of the welded joint of commercial titanium VT1-1. The plate welding with thickness 2 mm was manufactured butt in the medium of argon by the nonfusible tungsten electrode on copper block/backing and with copper tie plates. Uneven heating and cooling in the process of the formation of welded joint leads to the unhomogeneity of properties, and among other things electrochemical.

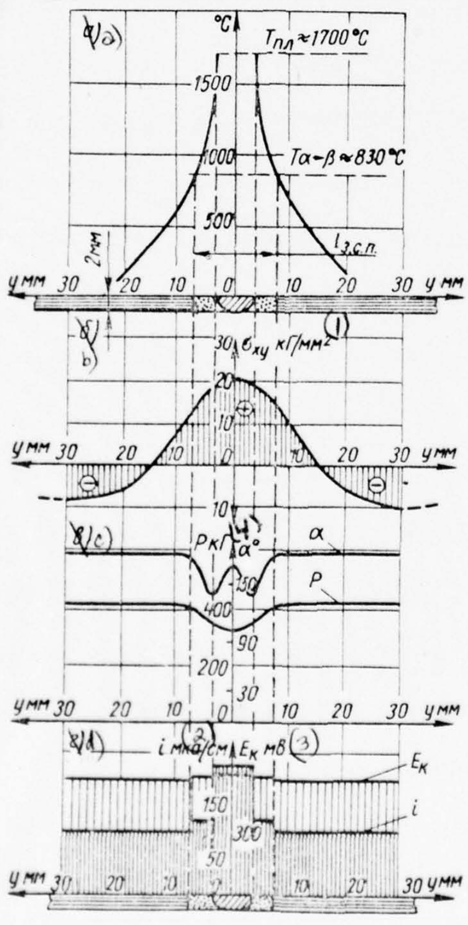

Fig. 2.

Fig. 2. The unhomogeneity of the properties of the welded joint of commercial titanium VT1-1: a) the distribution of the maximum temperatures in cross section at welding ($a_{з.с.п}$ - is a zone of structural transformations); b) the distribution of the longitudinal residual welding stresses σ_{xy} in the cross section of welded joint; c) the distribution mechanical characteristics with bending (P - peak load in kgf, α - bend angle in deg); d) is electrochemical unhomogeneity of welded joint during testing in 20o/o· to hydrochloric acid with room temperature (E - stationary potential in mV, i - anode current density in $\mu A/cm^2$).

Key: (1). kg/mm^2. (2). μA/cm. (3). mV. (4). kg.

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It is possible to separate three basic zones: a) the cast structure of weld, limited by dilution zone; b) the zone of structural transformations, limited by dilution zone and by zone on the boundary/interface, where the base metal did not undergo structural transformations. The maximum temperature on this boundary/interface comprises, according to the data of the oscillography of thermal cycles, for the alloy VT1-1 830-850°C; c) the base metal, which did not undergo transformations.

In weld and the adjacent zone appears the field of elongating residual welding stresses, which beyond the limits of the zone, heated below temperatures 300°C, transfer/convert to compressive.

Is characteristic the sharp nonuniformity of mechanical characteristics in welded joint during testing for static bending. Strength is decreased in the zone of structural transformations in comparison with the base metal and has a tendency toward decrease with coarsening from the base metal toward weld. A change in the plasticity, determined bend angle, has more complex character. The weakest zone is a dilution zone in connection with adverse structure and the increased impurity content.

In the simplest case in question is absent the chemical unhomogeneity of welded joint, since welding was done in inert atmosphere without additive. The measurement of stationary potentials in different zones showed that welding zone and the base metal they corrode with midpotential, which indicates the predominantly microlocalized character of corrosion. In connection with the unhomogeneity of welded joint on structure and the stressed state the rate of work of microcorrosion pairs, characterized by anode current density i μA/cm², is different for different zones. The rate of the corrosion of weld is considerably higher than the base metal. When the chemical unhomogeneity of welded joint is present, the picture macro- and the microelectrochemical unhomogeneity becomes more complex.

Very frequently welded constructions fail themselves not as a result of the anodic processes of the dissolution of metal, but as a result of the loss of strength and plastic properties during cathode processes. Is most dangerous hydrogen absorption in the process of corrosion (Fig. 3).

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The process of the liberation of hydrogen on cathode sections consists of following stages [3]:

a) dehydration of hydrogen ion, since during the dissociation of electrolyte hydrogen is located in solution in the form of the hydrated charged i/ns.

$$H^+ \cdot nH_2O \rightarrow H^+ + nH_2O;$$

b) attachment of an electron to the ion of hydrogen and formation of the atomic hydrogen

$$H^+ + e \rightarrow H;$$

c) the joint of hydrogen with the formation of the molecules of the hydrogen

$$H + H \rightarrow H_2;$$

d) formation of bubbles from the molecules of hydrogen;

e) the isolation/evolution of bubbles from the surface of metal.

During corrosion with hydrogen depolarization the hydrogen is found on the corrosive surface in the ionic, atomic and molecular states, which lead as a result of sorption processes to the hydrogen absorption of metal. By a characteristic example of the failure of welded joints as a result of the cathode process of saturation as hydrogen can serve the failure of some alloyed titanium alloys during corrosion in acid media [5]. The presence of martensite type adverse coarse-acicular structure along with the more intense work of microelements in weld and zone of structural transformations leads to the more intense hydrogen absorption of these zones in comparison with the base metal. Hydrogen absorption sharply decreases the strength and the plasticity of welded joint and it produces cracking under conditions of the stressed state.

In Fig. 4. shown is the effect of welding thermal cycle on hydrogen absorption and properties of the welded joint of the titanium alloy OT4. Corrosion tests were conducted in 20o/o to hydrochloric acid for 1550 h at temperature of 16°C. Analogous data were obtained during the weld test of steel Kh18N9T in 20o/o hydrochloric acid for 4300 h at temperature of 16°C (table).

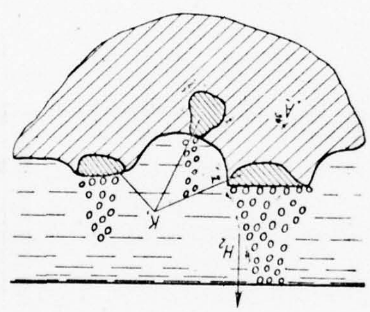

Fig. 3. The diagram of electrochemical corrosion with the hydrogen depolarization: A are anode sections; K - cathode sections.

Зона сварного соединения	Разрушающая нагрузка при изгибе в кГ		Угол загиба в град	
	Исходное состояние	После коррозии	Исходное состояние	После коррозии
Основной металл	374	365	180	180
Сварной шов	294	98	180	24

Key: (1). Breaking load with bending in kgf. (2). Bend angle in deg. (3). Zone of welded joint. (4). Initial state. (5). After corrosion. (6). Basic metal. (7). Welding seam.

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Mechanism of corrosion cracking. In practice are most widely known two cases of the corrosion of metal under stress, which is accompanied by the appearance of the corrosion crackings: a) the corrosion fatigue, which attacks feast joint action on the metal of cyclic load and the corrosive environment: b) corrosion cracking is the failure, which occurs under the simultaneous influence of corrosive environment and applied or residual voltages.

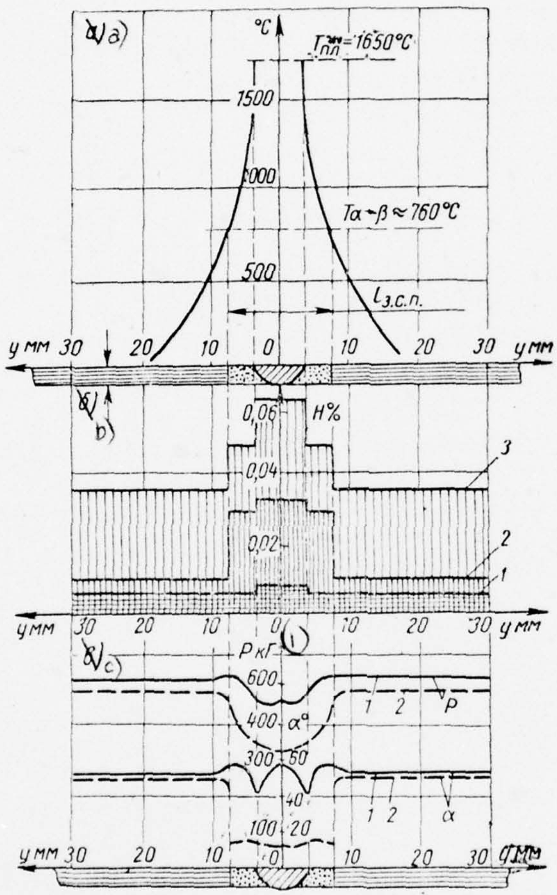
a)
°C
$T_{пл}$ = 1650°C
1500
1000
Tα→β ≈ 760°C
500
$l_{з.с.п.}$
y мм 30 20 10 0 10 20 30 y мм
b)
0,06
H%
0,04
0,02
3
2
1
c)
P кГ
600
400
α°
300
60
40
100
20
1 2 P
1 2 α

Fig. 4.

Fig. 4. The effect of hydrogen absorption in the process of corrosion on the properties of the welded joint of the alloy OT4: a) the distribution of the maximum temperatures in the cross section of welded joint; b) the content of hydrogen in the different zones of the welded joint: 1 is in the initial as-welded condition, 2. in central section/cut after corrosion tests, 3. at depth 0.1 mm from the surface of specimen/sample aftercorrosion tests; c) mechanical characteristics with bending; 1 - the initial state of welding, 2 - after corrosion tests.

Key: (1). kgf.

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To cases of corrosion cracking is related the so-called seasonal cracking of brasses; the alkali bitterness of boiler steel, intercrystalline corrosion cracking of aluminum alloys and noble metals; the intracrystalline corrosion cracking of magnesium alloys in the solutions of chlorides; the intracrystalline cracking of austenitic stainless steels in the media, which contain chloride or hydroxyl ions; the intercrystalline corrosion cracking of titanium alloys and their cracking due to hydrogen absorption during corrosion.

At present there is no unified theory, which explains the mechanism of the phenomenon. Corrosion cracking is caused by the joint action of two main factors: corrosive environment and tensile stresses. There are three groups of the theories, which explain the role of the basic factors of corrosion cracking [1, 6-11]:

1. Electrochemical theory of corrosion cracking. According to this theory the main reason for emergence and development of corrosion cracking is the process of electrochemical corrosion. Stresses accelerate the process of electrochemical corrosion in the apex/vertex of the developing crack.

2. Mechano-electrochemical theories. According to these theories crack initiation is caused by local electrochemical process; however, the main role in the development of crack is abstract/removed to the action/effect of stresses.

3. Theories, which consider the adsorptive phenomena during corrosion. These theories, besides corrosion and mechanical factors, consider the phenomena of the effect of strength reduction through adsorption.

The first two theories reflect special cases of corrosion cracking. More general character has electrochemical-adsorptive theory. However, these theories do not explain the phenomena of cracking by certain metals in the corrosion-active media as a result of the absorption of the products of corrosion with the formation of chemical compounds. An example of the cracking of the welded joints of the alloyed titanium alloys, caused by the formation of the hydride phase during hydrogen absorption in the process of corrosion with hydrogen depolarization, is given in work [5].

By analogous mechanism is possible the cracking of the structural hydride-forming metals - zirconium, niobium, tantalum - under conditions of corrosion with hydrogen depolarization, in superheated steam, water of supercritical parameters, with the radiolysis of water.

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The corrosion cracking is determined by the simultaneous course of the electrochemical, mechanical and sorption phenomena.

Sorption phenomena cause adsorption and absorbtive decrease in the strength and the facilitation of deformation with cracking.

Let us introduce the concept of the checking factor of corrosion cracking, in essence which determines emergence and the development of corrosion cracking. Depending on specific conditions (medium, material, the value and the form of stresses) checking it can be any of the basic factors of corrosion cracking, and, correspondingly, the mechanism of cracking will be different.

The role of each of the basic factors is changed depending on the stage of cracking. If the initial stage of the origin/conception/initiation of crack dominant role, as a rule, plays electrochemical process, then in the final stage of failure predominates mechanical effect, i.e., stress.

Affected sections of the surface of the loaded metal become stress concentrators. With localization of the process of corrosion and deepening of ulcers increases the stress concentration. Lots with the maximum stresses (bottom of ulcer) have more negative potential, i.e., they are the anodes; therefore corrosion ulcers are deepened before initiation of cracks (Fig. 5). In the process of emergence and developing crack the stress concentration causes the failure of protective film on the surface of metal, the structural transformations under the action/effect of the local plastic deformation and some other phenomena, which misalign potential in the apex/vertex of crack to disadvantage and they reinforce electrochemical unhomogeneity. Thus, the development of crack during the checking electrochemical process is caused by the anodic process, activated by the action of stresses. Under these conditions the role of sorption process consists in the superficially-adsorptive effect of a reduction in strength and facilitation of the deformation of metal in the apex/vertex of the developing crack.

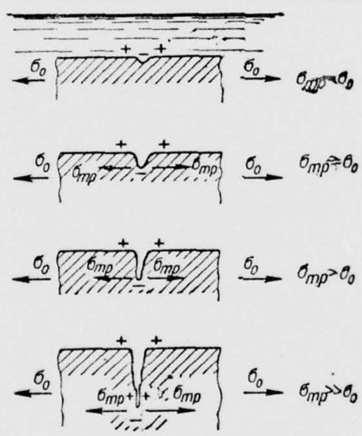

Fig. 5. Diagram of the development of crack with corrosion cracking.

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An example of this mechanism of failure is the corrosion cracking of titanium alloys in the bromine-methanol media and the nitric acid. Cracking occurs as a result of the selective intercrystalline corrosion, accelerated by the action/effect of the applied voltages. The analogous mechanism of cracking is drawn by the majority of the researchers for the explanation of the phenomena of the corrosion cracking of the stainless steel in chlorides.

An example of corrosion cracking with the checking sorption factor is the failure of the welded joints of the titanium alloys during corrosion with hydrogen depolarization in acid media [5] (Fig. 6). In this case the dominant role in failure belongs to the phenomena of the sorption of hydrogen during cathode processes. The failure of protective film during electrochemical corrosion creates prerequisite/premises for the intense adsorption of hydrogen by titanium. The adsorbed hydrogen enters into chemical interaction with titanium, forming hydride film. As a result of the diffusion of hydrogen through the hydride film. film in the volume of metal are formed hydrides of titanium, which are predominantly on boundaries of the grains and slip planes. Localization of electrochemical process contributes to localization of hydrogen absorption. The formation of hydrides on surface and the adjacent region leads to reduction in the strength surface conditions, concentration of stresses and the emergence of the initial microcracks under conditions of the stressed state.

In the zone of the apex/vertex of stress concentrator - to the developing crack - the processes of the sorption of hydrogen occur most intensely. This is caused by the following reasons: a) in the zone of crack is separated the increased quantity of hydrogen as a result of the work of microcorrosion cell/element - the bottom of crack - wall of crack; b) stress concentration in the apex/vertex of crack causes intensified diffusion of hydrogen into this zone, since hydrogen it has a tendency to diffuse into the most strained regions; c) as a result of the formation of hydrides of titanium during the intensive diffusion of hydrogen appear the secondary second-order stresses, which accelerate the process of diffusion, i.e., process it occur/flow/lasts autocatalytic. These phenomena lead to an abrupt change in the properties of metal and upon reaching of the critical for these conditions (form and stress level, the structure and the composition of metal and, etc) degree of hydrogen absorption to the development of crack under the action of the applied voltages. The stresses contribute to the emergence of microcracks and are the energy condition of developing main-line crack, localize corrosion process as a result of stress concentration and reinforce the processes of the local and common/general/total hydrogen absorption of metal.

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AD-A048 336 FOREIGN TECHNOLOGY DIV WRIGHT-PATTERSON AFB OHIO F/G 13/8
RELIABILITY OF WELDED JOINTS AND STRUCTURES (SELECTED ARTICLES)--ETC(U)
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The role of electrochemical process consists in the transport of hydrogen to the corrosive surface during cathode process, the upon acceleration of the process of failure as a result of the anodic dissolution of the apex/vertex of crack.

The necessary condition of emergence and developing corrosion cracking is a specific ratio between the rate of common/general/total corrosion and the rate of the development of the crack:

$k_{mp} \gg k_{o.\kappa}$ — cracking is,

$k_{mp} \leqslant k_{o.\kappa}$ — cracking no,

where k_{mp} is velocity of propagation of crack;

$k_{o.\kappa}$ - the rate of common/general/total corrosion.

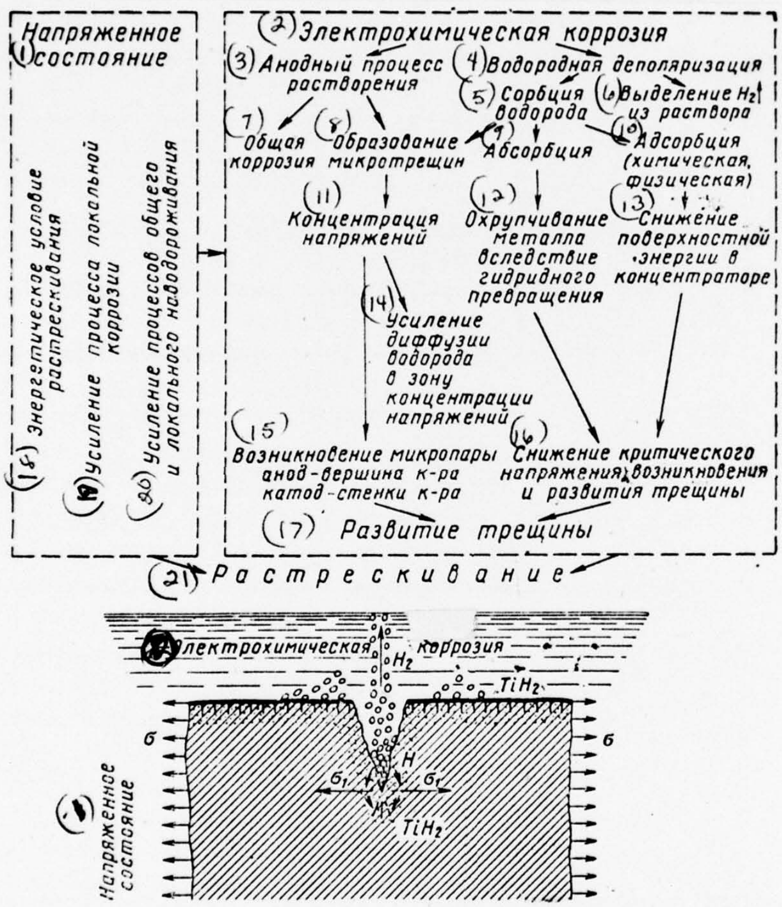

Fig. 6. Mechanism of the cracking of titanium alloys during corrosion with hydrogen depolarization.

Key (1). Stressed state. (2). Electrochemical corrosion. (3). The anodic process of dissolution. (4). Hydrogen depolarization. (5). Hydrogen sorption. (6). liberation of H_2 from solution. (7). general corrosion. (8). the formation of microcracks. (9). Absorptions. (10). Adsorption (chemical, physical). (11). Stress concentration. (12). Embrittlement as a result of hydride transformation. (13). Reduction in the surface energy in concentrator. (14). Strengthening of the diffusion of hydrogen into the zone of stress concentration. (15). Emergence microcells anode-apex/vertex is which cathode-wall is which. (16). Reduction in the breaking stress of emergence and development of crack. (17). Development of crack. (18). Energy conduction for spalling. (19). Intensification of the local corrosion process. (20). Intensification of the processes of general and local hydrogen absorption. (21). Cracking.

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If the metal of struts against corrosion (common/general/total and local), then corrosion cracking will not be.

Special feature/peculiarities of the corrosion cracking of welded joints. The mechanism of the corrosion cracking of welded joints does not differ in principle from the mechanism of the corrosion cracking of the base metal. However, welded joints possess a series of the specific special feature/peculiarities, which lower the stability of welded joints against corrosion cracking.

In light of the theory of corrosion cracking as failure, caused by the simultaneous effect of electrochemical, mechanical and sorption factors, by the special feature/peculiarities of welded joints, which lower the stability of welded joints against corrosion cracking, they are: 1) the increased thermodynamic instability, which leads to the increased electrochemical heterogeneity in comparison with the base metal; 2) the more complex and more adverse stressed state; 3) the possibility of the more intensive course of sorption processes. These special features of welded joints are caused by thermophysical processes during uneven heating and cooling metal during welding.

The structural, chemical, geometric unhomogeneity, caused by uneven heating, lead to the increased electrochemical heterogeneity of welded joint. The thermal process during welding determines the nonuniform distribution of the inherent stresses and the formation of temperature and residual stresses in welded constructions. The presence of its own residual stresses complicates the stressed state in welded construction and also increases the electrochemical heterogeneity of welded joints.

Depending on construction and the conditions of external loading in welded joints can appear the different stressed states:

$$1)\ \sigma_{вн}=0,\quad \sigma_{ост}=0;\quad 2)\ \sigma_{вн}>0,\quad \sigma_{ост}=0;$$
$$3)\ \sigma_{вн}=0,\quad \sigma_{ост}>0;\quad 4)\ \sigma_{вн}>0,\quad \sigma_{ост}>0,$$

where $\sigma_{вн}$ are stresses from external load;

$\sigma_{ост}$ - residual welding stresses.

Can appear the stressed states: mono-, two-, triaxial and different combinations from external load and residual welding stresses. For example, in the nozzle welded joint of the container, which works under pressure, the biaxial field of the residual of the welding stresses is combined with biaxial stresses from external load.

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In some corrosion-active media the residual the welding stresses, acting jointly with external load, sharply accelerate the process of cracking especially under conditions two- and of triaxial stressed state [13].

Relative to the rate of sorption processes in welded joints it is difficult to give unambiguous answer/response. However, in number of cases the presence of the strained structure of welded joint increases the rate of sorption processes, for example the more intense hydrogen absorption of the welded joints of titanium alloys in comparison with the base metal.

To corrosion cracking can have an effect the weld defects. Connection/inclusions can reinforce electrochemical heterogeneity, the flaw/defects of the form of weld; for example, poor fusions, as stress concentrators, can be the reason for the emergence of corrosion cracking.

Methods of an increase in the stability of the welded constructions against corrosion damage. To raise the stability of welded constructions against the corrosion failures is possible by the general methods of the protection of metal constructions from corrosion and by the special methods, which consider the special feature/peculiarities of welded joint.

At present for the protection of metal constructions from corrosion they apply:

1) protective coatings on organic basis (organic coating and

highly polymeric lubricants), on inorganic basis (oxide, phosphate, chromate, etc.) and metallic different types (metalization, hot, diffusion, cladding); 2) the treatment of corrosive environment - the neutralization and the deoxygenation of the liquid media, the application/use of a various kinds of inhibitors - the substances, which retard the rate of the corrosion of metal, etc.; 3) electrochemical protection (cathode) with the application/use of tread/protectors, electrochemical (anode) and protection from stray currents with the application/use of electrodrainage; 4) the development and the manufacture of the new structural metals of increased corrosion resistance; 5) rational construction and the operation of metallic constructions and parts.

The rational safety method of metals from corrosion from the positions of the electrochemical theory of corrosion is braking the checking factor of corrosion [3, 15].

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The value of the corrosion current, which determines the rate of corrosion, depends on four basic factors of the electrochemical corrosion: a) $E_K^0 - E_A^0$ - are differences in the initial potentials: the equilibrium potential of the cathode depolarizing process E_K^0 and of the anode reaction of the dissolution of metal E_A^0 under conditions of corrosion; b) the average cathode polarizability P_K; c) the average anode polarizability P_A; d) the ohmic resistance of the corrosion cell/element R.

These factors are bonded by the expression

$$I = \frac{E_K^0 - E_A^0}{P_K + P_A + R}.$$

The emf of corrosion cell/element $E_K^0 - E_A^0$ characterizes the degree of the thermodynamic instability of system; the denominator characterizes common/general/total kinetic braking system.

The rate of corrosion can be decreased by a reduction in the thermodynamic instability of system or increase in kinetic braking system because of braking cathode P_K and anode P_A processes and increases of the ohmic resistance of system R.

By the basic method of deceleration of the corrosion of welded joints and increase in the stability to corrosion failure under stress is the decrease in their thermodynamic instability, the decrease macro- and the microelectrochemical heterogeneity both the poured weld material and entire welded joint as a whole, the way:

a) decrease in the chemical unhomogeneity of welded joint; in the majority of cases is required the chemical composition of weld, identical for the chemical composition of the base metal;

b) decrease in the structural heterogeneity by the control of thermal cycles during welding, by change of crystallization conditions in the process of welding (modification, the "freezing" of bath, ultrasonic processing), by the application/use of heat, mechanical and thermomechanical treatment;

c) decrease in the unhomogeneity of the stressed state of the first and second gender in welded joint with the aid of heat, mechanical and thermomechanical treatment; improvement in the stressed state in welded joint by the rational construction of weldments; the release of the residual of the welding stresses by heat, mechanical or thermomechanical treatment; the creation of the compressive surface stresses by machining (rolling, shot peening);

Decrease in the mechanical and geometric unhomogeneity of welded joint can be reached because of rational technology of the preparation of welded joints without stress concentrators.

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ELIMINATION OF RESIDUAL DEFORMATIONS DURING THE WELDING OF SHEET PANEL CONSTRUCTIONS.

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During the manufacture of some sheet constructions widely is utilized spot welding. The volume of spot welding, for example during the manufacture of sheet panels, is 80-90o/o of volume of all welding work. One of the basic problems, which appear during the manufacture of panel constructions, is the straightening/trimming. Present article proposes to open the basic reasons for the formation of welding residual deformations and to nonmark some ways of fight with them in sheet panels.

Panel constructions represent the sheathing/skin, connected by spot welding with the batch of rigid cell/elements. For a rigidity apply the not connected stringers, preliminarily corrugates sheets (Fig. 1a and b). Of any strict sequence of the setting of spot welds, preventing or decreasing deformation, does not exist. They assume that for the prevention of the formation of "pops" or other local deformations welding one should conduct from middle to the edges of panel. However, this does not guarantee from the common/general/total carrier, frequently greater than buckling during welding in any another sequence.

The basic residual deformations of different panel constructions are the longitudinal, cross and diagonal sagging/deflections and the loss of stability. Loss of stability is extremely rare and appears only in the case of extremely low rigidity of weldment. The deformations of loss of stability can be removed by the post-welding rolling of weld zone - by the method, widely used in industry. True, the rolling of intermittent welds has a series of the special feature/peculiarities, at which let us pause.

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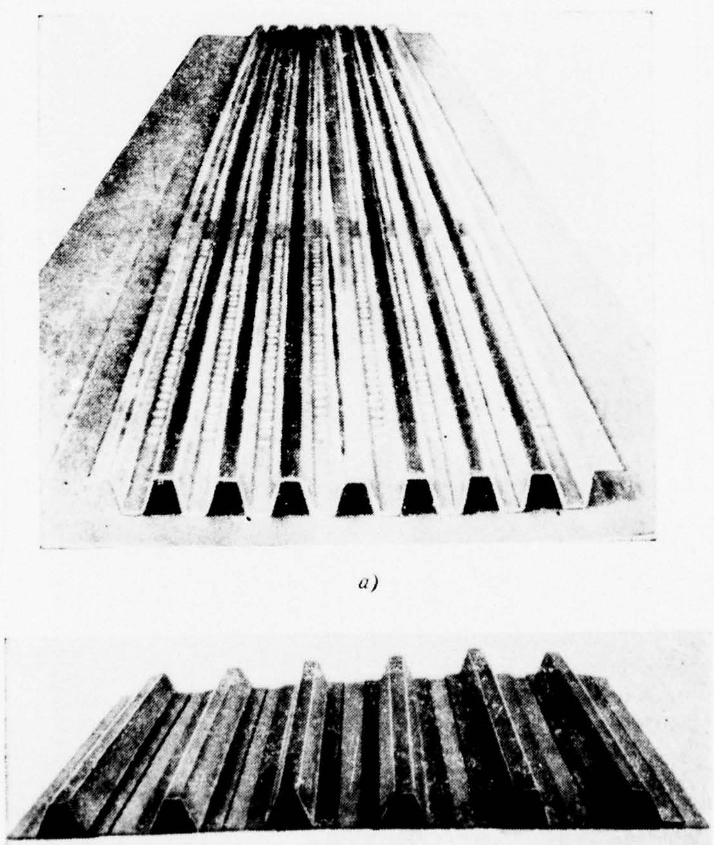
The appearing during welding cross sagging/deflection (Fig. 2) as show measurements, is uniform in width it can be prevented directly in the welding process, with the use of the attachments, which assign the sagging/deflection, reverse and equal in magnitude welding (Fig. 3a). It is possible also during welding to give to panels the local cross sagging/deflection (Fig. 3b), but in this case difficultly parameter determination of the deformation, which eliminates the formation of permanent deflection.

The most significant and difficult to remove are the longitudinal and diagonal deformations. the shrinkage of spot welds results in reduction in the intermittent weld along the length.



a)

b)

Fig. 1.

Fig. 1. Sheet panels with checkered plate (a) and with stringers (b).

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In weld zone appear after welding the residual tensile stresses, which reach maximum value directly on the axis of weld in the place of the setting of spot welds (Fig. 4). In the interval/gaps among points residual stresses are below. when selecting rolling schedules after welding it is necessary to be oriented toward the average value of the residual stresses in the central section of weld.

The given stress field obtained by calculation for flat sheets can be used for determining the middle stress level in the zone of rolling. The action/effect of the residual stresses in sheet panel constructions is equivalent to the noncentral load application. The inertia axis of panel is furnished somewhat higher than the axle/axis of the action/effect of residual stresses, as a result of which the upper filaments of stringers also prove to be under the action/effect of tensile stresses (Fig. 5a). The longitudinal sagging/deflection is not identical in the different section/cuts of panel even in such a case, when in each of the welds act equal residual stresses.

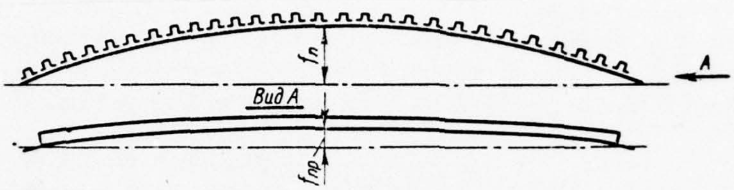

Fig. 2. The cross and stretch deformations of the panels, welded on the horizontal table: f_n is sagging/deflection in transverse direction; f_{np} - sagging/deflection lengthwise.

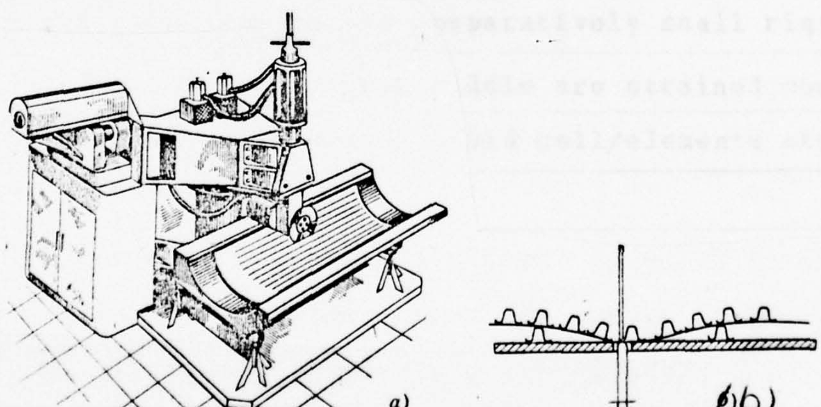

Fig. 3. the elimination of cross sagging/deflection during bench welding, which assign reverse sagging/deflection with the aid of special table (a) and the local bending (b).

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This is explained by the different rigidity of construction in different section/cuts in the welding process and by the dependence of shrinkage effort/force on the rigidity of section/cut, which grow/rises with stitching.

The profilogram of cylindrical panel (Fig. 5b) is constructed according to the results of direct measurements after welding (sequence of stitching - from middle to the edges of panel). For the larger clarity of the character of displacements the panel is conditionally depicted in plane. The shaded sections characterize the measured after welding deviation of the outline/contour of panel from the initial position. The having comparatively small rigidity edges of this panel during welding from middle are strained considerably more than in the case victuals of rigid cell/elements staggered.

With the rational sequence of stitching, which decreases the sagging/deflection 10-12 times, first are welded the extreme sections of panel, then panel they divide/mark off in width into equal parts (dotted lines in Fig. 5c), in each of which in rotation are applied the welds. The amount of the deformations of edge, which appear from the imposition of central welds, inversely proportional to the rigidity of boundary/edge section/cut. The general amount of deflection of edge is determined by the sum of the deformations of edge directly from edge joint and from the welds, arrange/located in the center section of the panel.

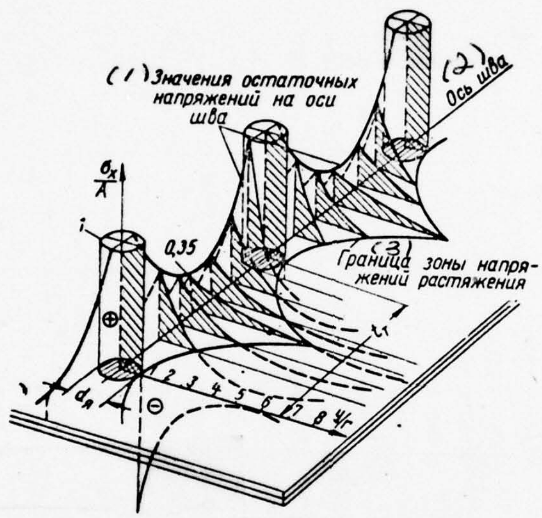

Fig. 4. The field of the longitudinal residual stresses of the single-row spot weld: t_T **is a step/pitch between points; r - the radius of spot weld.**

Key: (1). Values of residual stresses on the axis of weld. (2). Welding line. (3). Boundary of the zone of tensile stresses.

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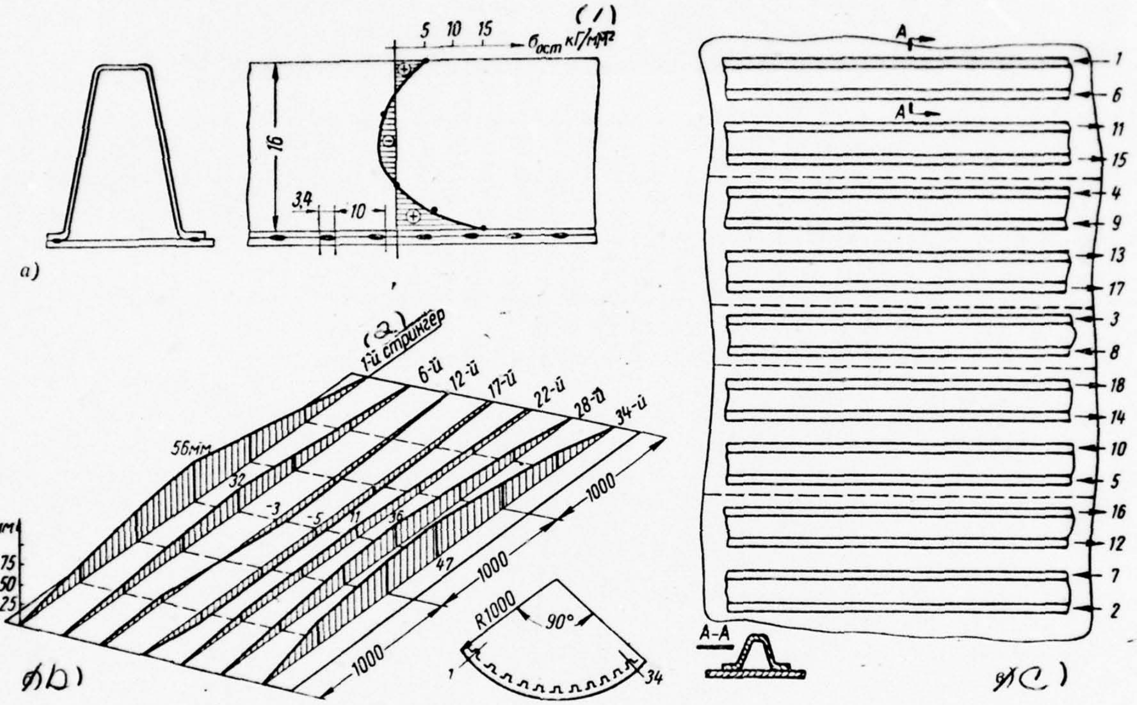
(1)
5 10 15
$\sigma_{ост}$ кГ/мм²
16
3,4
10
a)
(2)
1-й стрингер
6-й
12-й
17-й
22-й
28-й
34-й
56мм
32
-3
-5
11
36
47
f мм
75
50
25
1000
1000
1000
R1000
90°
34
б(b)
A
A
1
6
11
15
4
9
13
17
3
8
18
14
10
5
16
12
7
2
A-A
в(c)

Fig. 5

Fig. 5. Distribution of residual stresses according to height the flanges of stringer from the alloy OT4; by thickness 0.6 + 1.0 mm (a), the profilogram of the longitudinal sagging of welded panel (b) with cylindrical cross section (radius of curvature 1 m, length 3 m) and rational welding sequence of stringers (c).

Key: (1). kg/mm². (2). stringer.

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The portion/fraction of the deformations of edge of the imposition of the central welds the greater, the lesser the rigidity of the edge of panel. Therefore first of all is manufactured the welding of the edge of panel. However, no sequence of stitching makes it possible to completely remove the deformations of buckling, which appear from shrinkage.

For dealing with residual deformations, in particular for the prevention of their formation, it is expedient to utilize two known stages - rolling of weld zone or forging by electrodes. The second stage one should consider as the most advisable, since it makes it possible to avoid shrinkage. The mode/conditions of forging can be determined by calculation [1].

Forging is difficult in large-size sheet panels with tens thousand of points, weldable in series roller machines. The redesigning of such machines for a welding with forging leads to the new deformations - technological, which in seam welding machines are developed several times more powerful than on point. In this case for the elimination of deformation it is expedient to apply rolling. The width of the zone of rolling can be restricted by the diameter of spot weld.

Is developed procedure for the selection of rolling schedules. In this case the spot weld considers as continuous, with the determined middle level of the longitudinal residual stresses in the rolled zone. The pressure of rolling is selected according to the calculations, given in work [2]; the residual stresses are determined depending on the relation of the step/pitch of points toward their radius on curve/graph, constructed according to the results of the calculations (Fig. 6). Function A is numerically equal to the value of the longitudinal residual stresses in continuous (roller) weld and it comprises for an alloy OT4 35 kg/mm² for steel St. 3 21 kg/mm². The experimentally determined residual stresses in the specimen/samples, rolled under conditions, selected in accordance with this procedure, satisfactorily coincide with calculated (Fig. 7). The sequence of rolling substantially does not affect the process of the elimination of deformations. Welds can be rolled both from one edge of panel to another alternately and from middle to edges.

Along with the longitudinal sagging/deflection, in sheet panel constructions appears the diagonal sagging/deflection, which is the consequence of displacement during the welding of the parts to be connected (or, which is the same thing, "technological" deformations). The special feature/peculiarities of the formation of this type of deformations are examined in detail in work [3]. Therefore let us pause only at the rational methods of their elimination in connection with the constructions of average sizes (long than 2 m).

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Such constructions during welding can be rotated in horizontal plane with the aid of tilters, by applying any rational order of the setting of the points and by furnishing panel in the necessary position of the relative electrodes of welding sets.

Upon the consecutive setting of the points in one direction, the displacement of electrodes leads to one-sided bending. The amount of displacement depends neither on the rigidity of parts nor on the parameters of welding conditions [3], but it is determined by the relationship/ratio of the rigidities of the arms of welding set. The addition of shearing strains from isolated points leads to the longitudinal sagging/deflection. If we weld all welds in one direction, from one edge of panel to another, then appears diagonal sagging/deflection. The amount of deflection of each subsequent weld is equal to the sum of its own sagging/deflection and sagging/deflection, which arose in the section/cut in question from the imposition of all preceding/previous welds. Panel after welding is distorted.

The profilograms of panel made of steel VNS-2 in different cross sections (Fig. 8a) testify to considerable diagonal sagging/deflection; the longitudinal sagging/deflection virtually is absent. It is obvious that part of the welds must be welded in opposite direction. For panel constructions it is possible to recommend the sequence of welds, providing certain decrease in the deformations due to shrinkage and the elimination of deformation, called diagonal sagging/deflection (Fig. 5c).

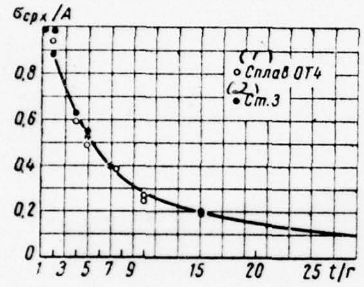

Fig 6.

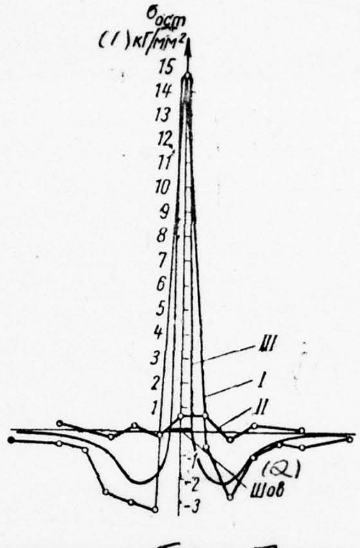

Fig. 7.

Fig. 6. Dependence of the value of the average longitudinal residual

stresses in single-row spot weld from the relation of step/pitch toward the radius of spot weld.

Key: (1). Alloy. (2). St.

Fig. 7. Average longitudinal residual stresses in the cross section of plates from the alloy OT4 with a thickness of 1.0 + 1.0 mm, welded by the spot welding: I and II - the experimental data; III - calculation data (I - measurement after welding, II - measurement after rolling with effort/force 950 kgf).

Key: (1). kg/mm^2. (2). Weld.

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During welding in the given sequence of the deformation of one direction they are compensated for by sagging/deflection due to contrary welds. In a number of cases to completely eliminate diagonal sagging/deflection, since, along with longitudinal displacement, occurs the transverse displacement of electrodes (rollers). Therefore the panels of average sizes it is expedient to weld in spot welders, divide/marking off all welds into equal sections 150-200 mm long. In this case occurs the compensation for the technological deformations, which accumulated in the first section, by the contrary deformations of the second section and, etc (Fig. 8b). This order of welding is more labor-consuming, but gives the smallest residual deformations and makes it possible to virtually prevent the formation of diagonal sagging/deflection.

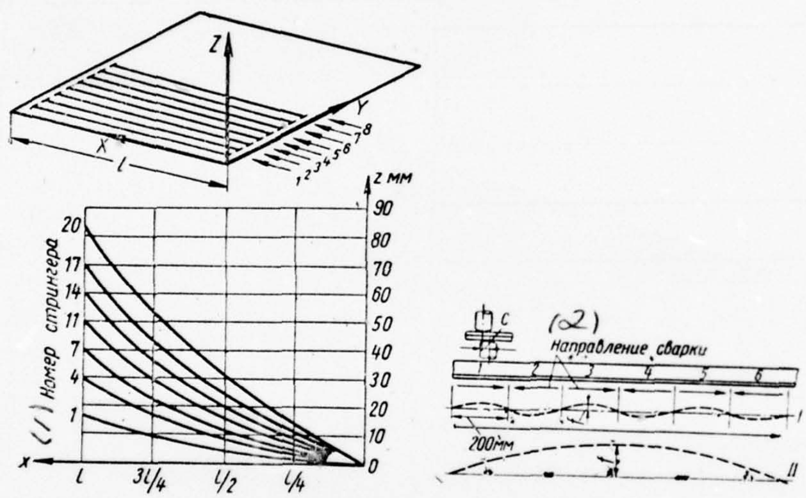

Fig. 8. The profilogram of the cross sections of the flat/plane panel, having diagonal (z) and longitudinal deflections (f) in weld zone from the displacement of the electrodes: I - shearing strains **are compensated for by welding sequence; II - shearing strains they**

are accumulated during welding in one direction; 1-6 - the sequence and direction of welding.

Key: (1). Number of stringer. (2). Direction of welding.

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ELIMINATION OF THE DEFORMATIONS OF LOSS OF STABILITY DURING PLATE WELDING WITH FRAMES.

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The joint of laminae with rigid frames frequently is encountered in practice. To nodes of such type, intended for the heavy-duty/critical constructions, are presented special requirements with respect to welding deformations, in particular for the presence of the deformations of loss of stability, which are generated after the joint of plate on outline/contour with frame. The elimination of deformations by known methods (setting of technological points, the rolling of welds after welding) labor-consuming or difficult to achieve in practice (for example, uniform heating plate to the value of the contraction, which appears from welding). At the same time left of the deformation of the loss of stability of plates without correction it should not be due to a reduction in the operating characteristics of the joint and due to the impossibility of the good-quality execution of some subsequent technological operations.

The proposed method of fight with deformations is intended for the plates, which are welded overlapping to the framework/body of frames. In this case by analogy with some known methods they use preliminary deformation. The scalded on outline/contour plate is hooked from four sides and is located under the action/effect of compressive forces. Distributed loads in the direction of axle/axes X and Y will be equal (Fig. 1)

$$q_x = \frac{P_{сж}}{\delta a + F_p}; \quad q_y = \frac{P_{сж}}{\delta b + F_p},$$

where $P_{сж}$ - the compressive force of one rectilinear weld;

δa, δb - the half of the cross-sectional area of plate in the direction of the action/effect of shrinkage effort/force;

F_p — area of the section/cut of frame.

In the calculations of constructions the solution of the problems of loss of stability is reduced to the determination of breaking stresses [1 and 2].

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In this case they are limited, as a rule, to the subcritical stage of the deformation of plates. In this work are examined the displacements of the surface of plate in the supercritical stage of deformation from the compressive strains of the edges of plate, caused by welding.

For the approximation of the symmetrically warped surface of plate are applied the double trigonometric series:

$$w = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} A_{mn} \cos\frac{m\pi x}{2b} \cos\frac{n\pi y}{2a}.$$

If we consider that the sagging of plate at point 0 (Fig. 1) is equal to f, and the relationship/ratio of the size/dimensions of sides a and b is such, that the loss of stability occurs with the formation of one half-wave of displacements and in direction X, and in direction Y, then the approximation for the deformed surface of plate, which satisfies conditions at edges (with x = b and y = a w = 0) will be [2]

$$w = f \cos\frac{\pi x}{2b} \cos\frac{\pi y}{2a}. \qquad (1a)$$

the components of displacement u and v into the central plane of plate can be determined in the following form:

$$\left.\begin{aligned} u &= C_1 \sin\frac{\pi y}{a} \cos\frac{\pi x}{2b} - e_y y; \\ v &= C_2 \sin\frac{\pi x}{b} \cos\frac{\pi y}{2a} - e_x x, \end{aligned}\right\} \qquad (1б)$$

where C_1 and C_2 - constants, determined from the conditions of the minimum of the strain energy of plate;

e_x and e_y are deformations of the contraction, determined from the character of action/effect and value of shrinkage effort/force.

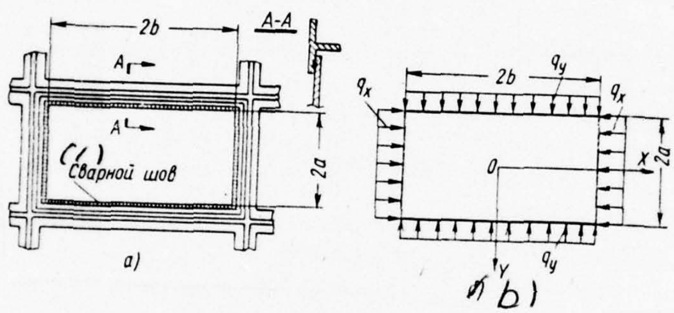

Fig. 1. Joint of plate with frame framework/body (a) and the circuit of the action/effect of loads after welding (b).

Key: (1). Weld.

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The components of deformations in the central plane of plate we determine by the known formulas:

$$\left.\begin{aligned}
\varepsilon_x &= \frac{\partial u}{\partial x} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2;\\
\varepsilon_y &= \frac{\partial v}{\partial y} + \frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2;\\
\gamma_{xy} &= \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} + \frac{\partial w}{\partial x}\cdot\frac{\partial w}{\partial y}.
\end{aligned}\right\} \qquad (2)$$

Strain energy P calculate in accordance with the expression

$$P = \frac{\pi^2 abf^2 D}{32}\left(\frac{1}{a^2}+\frac{1}{b^2}\right)^2 + \frac{Gh}{1-\mu}\int_{-a}^{+a}\int_{-b}^{+b}\times$$
$$\times\left[\varepsilon_x^2+\varepsilon_y^2+2\mu\varepsilon_x\varepsilon_y+\frac{1}{2}(1-\mu)\gamma_{xy}^2\right]dx\cdot dy, \qquad (3)$$
$$D = \frac{Eh^3}{12(1-\mu^2)}, \quad G = \frac{E}{2(1+\mu)},$$

where h - the thickness of plate.

Utilizing expressions (1) and (2), we solve equation (3) and find constant C_1 and C_2 from the conditions

$$\frac{\partial P}{\partial C_1} = 0; \quad \frac{\partial P}{\partial C_2} = 0.$$

Amount of deflection f we find from the relationship/ratio

$$\frac{\partial P}{\partial f} = 0,$$

$$f = \sqrt{\frac{H}{\frac{\pi^4}{256ab}\left(9\frac{a^2}{b^2} + 9\frac{b^2}{a^2} + 2\right)}},$$

where

$$H = \frac{\pi^2}{2}\left(\frac{a}{b}e_x + \frac{b}{a}e_y\right) - \frac{\pi^4 ab}{16}\left(\frac{1}{a^2} + \frac{1}{b^2}\right)^2 + \\ + \mu\frac{\pi^2}{2}\left(\frac{a}{b}e_y + \frac{b}{a}e_x\right) + C_1\frac{\pi^2}{3}\left(\frac{2b}{a^2} + \frac{1-3\mu}{2b}\right) + \\ + C_2\frac{\pi^2}{3}\left(\frac{2a}{b^2} + \frac{1-3\mu}{2a}\right);$$

$$C_2 = \frac{R}{\left(\frac{16}{9}\right)^2(1+\mu^2) - 4\pi^4\left(\frac{a}{b} + \frac{1-\mu}{8}\cdot\frac{b}{a}\right)\left(\frac{b}{a} + \frac{1-\mu}{8}\cdot\frac{a}{b}\right)},$$

where

$$R=\frac{8\pi^2f^2}{27}\left(\frac{2b}{a^2}+\frac{1-3\mu}{2b}\right)(1+\mu)-$$
$$-\frac{\pi^4f^2}{3}\left(\frac{2a}{b^2}+\frac{1-3\mu}{2a}\right)\left(\frac{b}{a}+\frac{1-\mu}{8}\cdot\frac{a}{b}\right);$$
$$C_1=\frac{\frac{\pi^2f^2}{6}\left(\frac{2b}{a^2}+\frac{1-3\mu}{2b}\right)-C_2\,\frac{16}{9}(1+\mu)}{2\pi^2\left(\frac{b}{a}+\frac{1-\mu}{8}\cdot\frac{a}{b}\right)}. \qquad (4)$$

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The constructed according to formulas (4) dependences (Fig. 2) for plates with ratio b/a = 1.25 show a change of the sagging/deflection in point 0 with the identical value of contraction e_x and e_y in both axle/axes.

From the theory of plates known that with the smallest breaking stresses loses stability the plate with ratio b/a, equal to integer, in particular square plate. Therefore we will be restricted subsequently to the examination of precisely square plate; in this case

$$f=\sqrt{\frac{6,42a^2(e_x+e_y)-4,058h^2}{5,688}}. \qquad (5)$$

For the analysis of the deformations of rectangular plate it is possible to utilize relationship/ratios (4) and (5), obtained for the plates of square form, since the disregarded amount of deformation exceeds the resistance to deformation of loss of stability. The amount of critical relative compressive strain can be determined from the condition of the equality of zero numerator of expression (5). Accepting $e_x = e_y = e$, we obtain critical compressive strain:

$$e_{\kappa p} = 0{,}316 \frac{h^2}{a^2}. \qquad (6)$$

For the selection of the amount of preliminary deformation it is necessary to know the deformations, caused by welding. For some special cases in specimen/samples is determined the shrinkage effort/force.

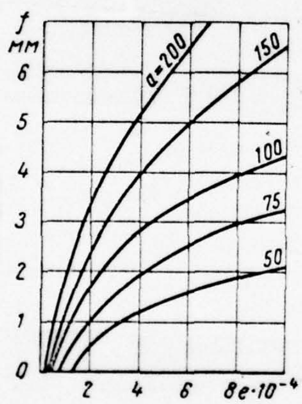

Fig. 2. Dependence of the sagging of plate due to relative compressive strain.

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In this case are establish/installed the area of the zone of plastic deformations and the average value of the residual stresses σ_{ocm} in this zone. Welding compressive strain

$$e_{cs} = \frac{\sigma_{ocm} F_{n\Lambda}}{Eha} (1 - \mu^2), \quad (7)$$

where $\sigma_{ocm} F_{n\Lambda}$ - the shrinkage effort/force of weld;

ha - the cross-sectional area of plate and frame.

Specifically, during the welding of steels VNS-2 (martensite class) and VNS-5 (austenite-martensite class) 1.0-1.0 mm thickness $\sigma_{ocm} \approx 3300$ kgf/cm², a $F_{n\Lambda} \approx 10$ мм² (Fig. 3). For a plate with side 2a = 200 mm the compressive strain from welding e = $1.5 \cdot 10^{-4}$ exceeds almost 5 times the amount of ultimate strain in formula (6), equal to $0.316 \cdot 10^{-4}$.

In order to avoid the deformations of loss of stability, it suffices evenly to elongate the sheet before welding in the direction, opposite to the action/effect of shrinkage effort/force to value $e_{cs} - e_{\kappa p}$. For this can be used the displacement of electrodes [3] in spot welders, because of which it is easy to carry out the necessary interference of sheets with clamp. In this case the relative displacement of electrodes with clamp must be 2-2.5 times greater than value $e_{cs} - e_{\kappa p}$, since to carry out an uniform elongation of plate in entire width with clamp is virtually difficult.

Interference is made as follows. First they tack/catch one of the edges (for example, edge 1 in Fig. 4), the node to be welded with clamp can occupy arbitrary position relative to the arms of spot welder. Then they tack/catch opposite edge 2, but in this case node must be arranged between the arms of machine in such a way that the displacement of electrodes would lead to the interference of plate. For this it is necessary to preliminarily determine the direction of the displacement of electrodes.

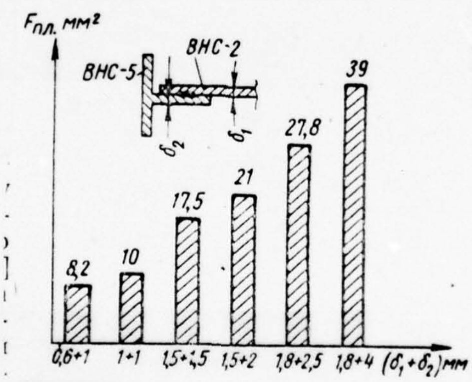

Fig. 3. Experimental values of the area of the zone of plastic deformations during the seam welding of steels VNS-2 and VNS-5.

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This can be carried out not only by direct measurement [3], but also by the indirect-welding of two laminae of small rigidity, moved to the value of the step/pitch after the welding of each point in determinate direction (into the outline/contour of the machine or from the outline/contour of machine). The size/dimensions of plates can be constants, since the amount of the relative displacement of electrodes depends only on the relationship/ratio of the rigidities of the arms of machines. For example, the plates 300 x 15 x 0.6 mm in size/dimension are welded with step/pitch 10 mm. If the bending of plates occurs with their feeding into machine in the manner that it is shown in Fig. 5a, then the arrangement of weldment in the outline/contour of machine must correspond to its arrangement in Fig. 6a. But if specimen/sample is bent to opposite side (Fig. 5b), then the node to be welded must be turned in horizontal plane to 180°. With the clamp of edges 3 and 4 (Fig. 4) is utilized usually the same principle, as for edge 2.

The elongation of plate partially is removed during welding. In the case of the sufficient displacement of the electrodes of loss of stability it will not occur.

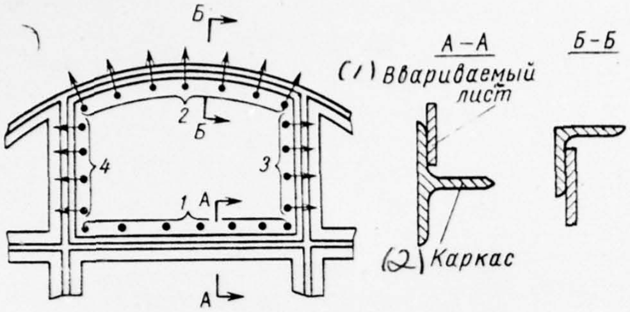

Fig. 4. Sequence of the clamp of plate to the framework/body of frame.
Key: (1). Welded sheet. (2). Framework/body.

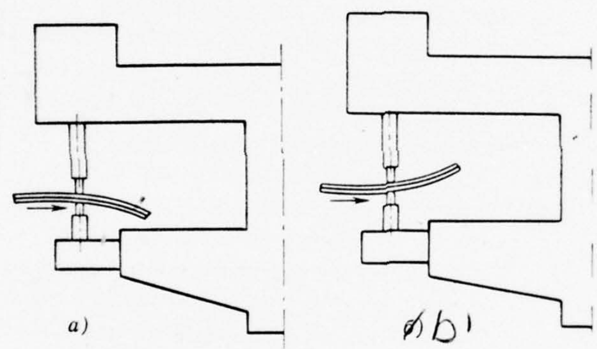

Fig. 5. Character of the sagging/deflection of specimen/samples in the case of the larger rigidity of the upper arm (a) or of the larger rigidity of lower arm (b).

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During a change in the rigidity of arms can be changed the amount of the relative displacement of electrodes, which is important for the safeguard for necessary interference [3]. Relative displacement Δ leads to completely determined sagging/deflection f of control specimen/samples. For achievement of the necessary displacement it is necessary that amount of deflection will be 1.5-2 times more than the value, obtained from the approximation formula

$$f=\frac{t\delta}{\Delta}\left(2-\sqrt{3-\cos\frac{n\Delta}{2\delta}}\right),$$

where Δ - the relative displacement of electrodes;

t - the step/pitch between points;

δ - the thickness of one sheet (are welded the specimen/samples of identical thickness);

n - a quantity of spot welds, between which it is determined the sagging/deflection of specimen/sample.

By changing the rigidity of arms, it is possible to select the necessary amount of deflection of specimen/sample f, and respectively also displacement Δ and, by applying the described method, to avoid the formation of the deformations of loss of stability. However, the exaggerated interference of sheets, obtained as a result of the relative displacement, which considerably exceed the values, sufficient for the prevention of deformations, is undesirable, since it can lead to high tensile stresses in sheets on line of weld.

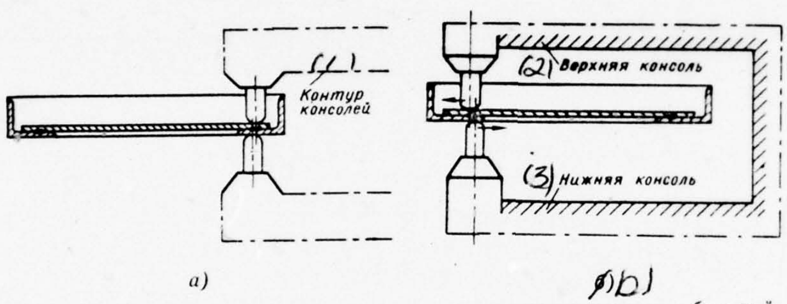

Fig. 6. Arrangement of node with the clamp of plate to frame with the greater rigidity of the upper arm (a) and of the smaller rigidity of the upper arm (b).

Key: (1). Outline/contour of the arms. (2). Upper arm. (3). Lower arm.

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IMPROVEMENT IN THE WELDABILITY OF THE MATERIAL SAP.

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As a result of the work, carried out in the MATI together with other organizations, it was establish/installed that the material of SAPs to be welded can be obtained by carrying out the high-temperature annealing of the blanks of SAP with their subsequent deformation [1, 2].

In our opinion, during this special treatment of material they are solved two basic questions: the redistribution of oxides of aluminum (failure of oxide framework/body) and the distance/removal of the sources of gas [2]. The material of SAPs, manufactured according to common technology [1], cannot be welded by the methods of fusion welding [1, 2].

FOOTNOTE [1]. The maximum temperature of heating blanks during the manufacture of common SAP does not exceed 450-500°C. ENDFOOTNOTE.

During the arc welding of this material the arc burns unstably, and the added metal is thrown out from bath, forming on edges the runs, affected by pores.

The annealing cf briquettes at temperature of 600-610°C with the subsequent deformation makes it possible to sharply improve the weldability of SAP. During the welding of this material the arc burns stable and bead joint is form/shaped normally. However, the strength of welded joints turns out to be very low and does not exceed 15-25o/o of the strength of material. During a further increase in the temperature of the annealing of the briquettes of SAP the weldability of material is improved; the relative strength of welded joints grow/rises (Fig. 1). During the welding of the sheets, manufactured from the briquettes of SAP, passed annealing at temperature of 650°C, the relative strength of joints reaches 45-50o/o.

As a result of the annealing of briquettes at the melting point of aluminum (660°C) is sharply improved the weldability of SAP and the relative strength of the joints, obtained during the welding of this material, it approaches 85-90o/o.

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The studies of the welded joints, obtained during the welding of the sheets of the SAP, manufactured from the briquettes, to annealed at different temperature, it will make it possible to reveal in the zone of the vacuum of gas origin (Fig. 2) near the weld. The total void content with an increase in the temperature of annealing regularly decreased (Fig. 3). during the comparison of the curves of the relative strength (see Fig. 1) and of the total void content (Fig. 3) of welded joints it is possible to note that the shape of the curve, especially in the region of the melting point of aluminum, considerably differs. Specifically, on curved total void content there is no jump at temperature of 660°C. This fact attests to the fact that the properties of the welded joints, obtained during the welding of SAP, depend not only on the total volume of the generating vacuums, but also on a series of other factors.

The basic source of the gases in SAP is the crystallization moisture of hydroxide of aluminum, which is contained in material [2, 3]. According to the data of some authors [3], this moisture is retained to temperature of 600°C. The conducted by us investigations in the vacuum extraction of aluminum foil showed that the crystallization moisture is retained up to the temperature, close to the melting point of aluminum. For the refinement of the temperature of decomposition of the being in SAP moisture of vacuum extraction at temperature of 700°C were subjected the specimen/samples of SAP, manufactured from the briquettes, passed the annealing at temperature of 590-600, 640, 650, 660^{+5}, 700 and 750°C.

The volume of the hydrogen, which separated during extraction, was determined by the formula

$$v_{H_2} = \Sigma_{H_2} - Sa_{H_2},$$

where v_{H_2} is a volume of the "internal" hydrogen, which separated directly from specimen/sample, in cm^3;

Σ_{H_2} - the total volume of the hydrogen, which separated during extraction, in cm^3;

S - the surface of specimen/sample in cm^2;

$\bar{a}_{H_2}$ - the volume of the hydrogen, which separated from the unit of the surface of specimen/sample, in ml/cm^2.

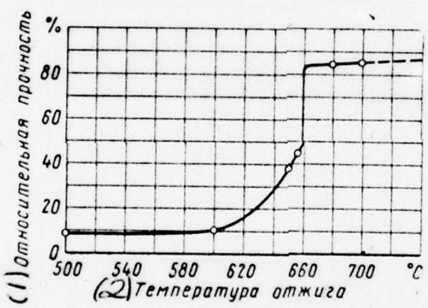

Fig. 1. The temperature effect of the annealing of briquettes on the relative strength of the welded joints, obtained during the argon-arc welding of SAP.

Key: (1). Relative strength. (2). Temperature of annealing.

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Fig. 2

Fig. 2. Pores, which are generated in the weld-metal zone near the weld, obtained by the argon-arc welding of the SAP, past the different temperature of the annealing of briquettes; x 70; a). 600°C; b). 650°C; c). 680°C.

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From the obtained results (Fig. 4) it follows that the content of the gases in SAP sharply is decreased with an increase in the temperature of the annealing of briquettes to 630-640°C. During a further increase in the temperature of the annealing of briquettes up to temperature of 660°C content of gases in material is changed less sharply and higher than the melting point of aluminum remains constant. This makes it possible to assume that in the process of the annealing of briquettes at the melting point of aluminum occurs virtually the full/total/complete decomposition of the crystallization moisture of hydroxide of aluminum. The hydrogen, which is contained in SAP, manufactured from the briquettes, passed annealing at temperature below 660°C, is present in the dissolved state in aluminum matrix/die, in the closed discontinuities and is located in bound state in the residue/remainders of hydroxide of aluminum.

During the welding of this material due to a sharp increase in the temperature in welding zone (800-900°C) occurs the violent decomposition of the residue/remainders of moisture and expansion gas, that is located in discontinuities. This leads to a considerable increase in the pressure in the closed vacuums. The latter, expand, destroy metal with the formation of "torn" pores, strains and cracks (see Fig. 2a and b). To the appearance of the flaw/defects indicated contributes the fact that the reaction of moisture with aluminum especially intensely passes in the places of the accumulation of hydroxide, i.e., in sections with weakened communication/connections between particles.

In SAP, manufactured from the briquettes, passed annealing at temperature higher than the melting point of aluminum, crystallization moisture, apparently, is absent and hydrogen is located in vacuums at insignificant pressure as a result of its dissolution in the process of annealing in liquid aluminum and of an increase in the vacuums in volume.

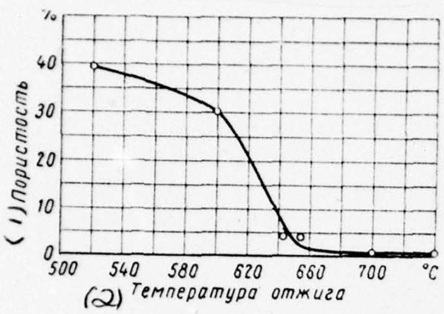

Fig. 3.

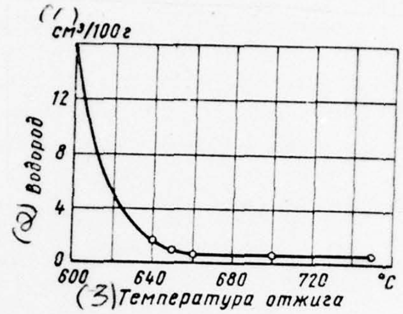

Fig. 4.

Fig. 3. Total porosity of **joints from SAP during argon-arc** welding in **temperature** dependence of the annealing of briquettes.

Key: (1). Porosity. (2). Temperature of annealing.

Fig. 4. Quantity of hydrogen, which separates during the vacuum extraction of SAP, in temperature dependence of the annealing of briquettes.

Key: (1). cm³/100g. (2). Hydrogen. (3). Temperature of annealing.

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In connection with this during the welding of SAP, manufactured from the briquettes, to annealed at temperature higher than the melting point of aluminum, the formation of strains and "torn" pores is eliminated and possibly only the formation of the pores of spherical form (see Fig. 2c), not exerting a substantial influence on the strength of material. The abrupt increase in the strength of welded joints from the briquettes, to annealed at temperature higher than the melting point of aluminum (see Fig. 1), in our opinion, completely it is possible to explain by the smaller value of the pressure of hydrogen in the closed discontinuities. It is possible that an additional improvement in the technological weldability of materials is connected also with an increase in the metallic bonds between single aluminum particles, the replacement of the deformed grains poured and with other factors.

On the basis of the findings it is possible to draw the conclusion that for obtaining SAP, which possesses a good technological weldability, the annealing of briquettes must be conducted at temperature higher than the melting point of aluminum (660-670°C). The application/use of a vacuum annealing of briquettes makes it possible to lower the necessary temperature of annealing. Thus, for instance, material with a good technological weldability was obtained with the annealing of briquettes in vacuum at temperature of 650 + 10°C. This can be explained by the following reasons. At the temperature of annealing, close to the melting point of aluminum, in material remains a very insignificant quantity of

moisture, capable during prolonged **reaction with aluminum** to separate not more than 0.5-0.6 $cm^3/100$ g of hydrogen. At the same time a quantity of dissolved in aluminum matrix/die hydrogen as a result of its partial removal from solution does not exceed ~0.3 $cm^3/100$ g, i.e., approximately 2 times is less than its equilibrium concentration in liquid aluminum (with T = 660°C and $p_{H_2} = 1$ at).

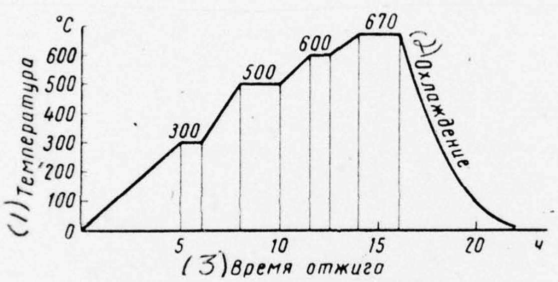

Fig. 5. Stepped mode/conditions of the high-temperature annealing of the cold-pressed briquettes of SAP.

Key: (1). Temperature. (2). Cooling. (3). Time of annealing.

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The generating in the welding process atomic hydrogen can be dissolved in liquid aluminum. Part of the hydrogen, which did not have time to be dissolved, will not be able to cause large pressure in discontinuities. The probability of the formation of strains and cracks sharply decreases. With the high-temperature annealing of briquettes, especially large size/dimensions, frequently are formed the cracks. These cracks affect adversely the stability of the mechanical properties of the semi-finished products of weldable SAP.

In the opinion of the authors, by the basic reason for the appearance of cracks in briquettes is too violent a gas evolution.

Mechanical properties of the joints without the removed strengthening, obtained during the automatic argon-arc welding of sheets SAP-1S butt with the application/use of a filler rod from the alloy AMg6.

(1) Толщина листа в мм	(2) Сварка	(3) Темпера-тура ис-пытаний в °C	(4) Предел проч-ности при растяжении $\sigma_в$ в кГ/мм²	(5) Относи-тельная прочность в %	(6) Угол за-гиба в град	(7) Примечание
1,5	(8) Односторонняя, неплавящимся электродом	20	24,4—26,6 / 25,1	82		
		350	9,3—9,7 / 9,5	—	—	—
		500	4,1—4,4 / 4,3	100		
	(9) Двусторонняя, неплавящимся электродом	20	27,1—28,1 / 27,9	93	30—109 / 93	(10) Конструктивная прочность бачков ~24 кГ/мм²
		500	3,3—3,6 / 3,5	100	—	—
		20	28,4—30,1 / 29,4	100	—	(11) Двухосное напряженное состояние
	(12) Односторонняя, плавящимся электродом	20	25,8—27,1 / 26,6	90	82—90 / 86	—
		500	3,5—3,9 / 3,7	100	—	—
3,0	(13) Односторонняя, с принудительным формированием шва	20	23,4—24,8 / 24,0	90	—	(14) Усиление снято
			25,1—26,7 / 26,3	100	—	—

Key: (1). Thickness of sheet in mm. (2). Welding. (3). Temperature of tests in °C. (4). Tensile strength in σ_B kg/mm². (5). Relative strength in o/o. (6). Bend angle in deg. (7). Note. (8). one-sided, by nonconsumable electrode. (9). Bilateral, by nonconsumable electrode. (10). Structural strength of small reservoirs ~24 kg/mm². (11). Biaxial stress. (12). One-sided, by consumable electrode. (13). One-sided, with the forced formation of weld. (14). strengthening is removed.

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The rate of formation of gases with annealing in its initial stage reaches ~120 cm³/100 g per minute. Considerable deceleration of the formation of gases (to 10 cm³/100 g per minute) reached by conducting high-temperature annealing under the stepped conditions with a gradual rise of temperature (Fig. 5). On this technology on one of the enterprises were made the industrial batches of the sheets of SAP (SAP-1S, SAP-2S), of large-size briquettes. Semi-finished products from weldable SAP possess high mechanical properties at room and elevated temperatures, they have high plasticity and contain an insignificant quantity of gases (less than 0.7-0.9 cm³/100 g).

The weakest section of the welded joints, obtained during the welding of SAP, is the section of the zone of material near the weld, heated during welding to temperature higher than the melting point of aluminum [2]. In this section melts the aluminum basis of material and they manage to pass the processes, which lead to the coarsening/consolidation of oxide particles. For obtaining welded joints with the maximum strength the welding one should conduct in possibly more arduous conditionss. In this case it is desirable that the cylinder of weld would cover the most weakened section of the zone of welded joint (see the Table) near the weld.

Conclusions.

1. The temperature of the annealing of briquettes exerts essential effect on the weldability of the manufactured of them semi-finished products.

2. The best technological weldability possess the semi-finished products, manufactured from the briquettes, thrown down to annealing at temperatures higher than the melting point of aluminum.

3. The application/use of a vacuum makes it possible to lower the temperature of the annealing of briquettes to 650°C and to keep a

good technological weldability of material.

4. In order to prevent the cracking of briquettes, it is expedient to apply the stepped annealing, which makes it possible to regulate the rate of formation of gases at different temperatures.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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