TECHNOLOGICAL STRENGTH AND ANALYSIS OF CAUSES OF WELDABILITY DETERIORATION AND CRACKING

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Criteria for evaluation of sensitivity to hot and cold cracking by different methods applied to determine technological strength were considered. Dependence of the sensitivity of material to cracking on its degradation was evaluated by the Varestraint-Test method. It is shown that cracking in all cases is caused by degradation of the material in certain temperature conditions and stress-strain state.

Keywords: *weldability, degradation, thermal stress, hot cracks, cold cracks, technological strength, test methods, brittle temperature range*

The heterogeneous «heating ↔ cooling» cyclic temperature effect leads to formation of thermal stresses in a welded joint. The presence of this state, along with probable structural changes of material, local deformation processes and residual stresses, causes substantial deterioration of properties of the material of a joint, i.e. its degradation. Different welding technologies may cause different degradation levels [1], which, according to the data of studies [2, 3], can serve as a criterion for evaluation of weldability. Obviously, if the material of the joint reaches the level of degradation that is higher than the tolerable one, this will lead to irreversible changes in its properties, such as cracking and fracture of the joint, or to its inadmissible performance.

In the last years, researchers have developed various technological strength test methods, which allow evaluating the sensitivity to hot and cold cracking in individual regions of a welded joint, or crack resistance of the entire joint [4–12]. These methods induce a limiting stress-strain state in the weld and joining zone, in which the degradation effects show up in metal. Technological strength takes into account only the material and technology, i.e. it considers only the possibility of formation of a joint, and ignores the factors of fitness of the resulting properties for the specified service conditions. Allowance for the latter factor is a necessary condition for evaluation of weldability [1]. However, it is beyond the scope of this article.

Consider some methods used to evaluate the technological strength during the solidification process (hot cracks) and their criteria.

The technological tests were developed to simulate conditions taking place in fabrication of real welded structures, e.g. multilayer welds in welding and cladding, and circumferential welds in welding or welding-in of pipes. The absence of the crack-type defects in test samples was indicative of a good weldability of metal, which made it possible to come to welding of real parts and motivate adequacy of the chosen welding technologies and consumables.

The qualitative tests for evaluation of the sensitivity to hot cracking include the following: «circular patch weld» [4], criterion of the presence or absence of macro- or microcracks; test specimen BWRA (British Welding Research Association) with a circumferential multilayer weld for austenitic steels [5], criterion of the presence or absence of cracks in the multilayer weld and HAZ metal; Kihlgren–Lacy specimen [5] — presence or absence of cracks in the multilayer weld; H-specimen [5] — presence or absence of macro- or microcrack in the third test weld; and T-specimen [6] — presence or absence of crack in the test weld.

The «semi-quantitative» tests [4] for evaluation of the sensitivity to hot cracking include the following: Kautz specimen [5] — the sensitivity to hot cracking is considered moderate if the total length of the cracks in the fourth test weld is not in excess of 25 mm; Huxley specimen [5] — depending on a particular case, a criterion can be the average length of a crack in the weld, or the average crack length to section length ratio; cruciform thin-sheet specimen [5] — ratio of the length of the welds with cracks to the total length of the welds, Braun–Boveri specimen [5] — quantity and length of cracks in the welds; segmented-groove circular restraint specimen [7] — total crack length to weld length ratio; Tekken specimen with slots [5], Houldcroft cracking test, circular patch specimen, and U.S. Navy circular-patch specimen [7] — crack length to total weld length percentage ratio.

Alloys and welding consumables are investigated, and welding parameters and conditions are optimised by using the qualitative and semi-quantitative tests. The evaluation criteria are presence or absence of hot cracks and their quantity, and absolute or relative length of cracks. This type of the tests characterises properties of alloys in terms of their technological strength, but does not allow discriminating its components, such as strength and ductility in the crack zone, shape and temperature limits of the ductility-dip range (BTR, DTR). That is, these tests fix only the fact of the presence of cracks at specified technological parameters in metal investigated, but they do not consider temperature and deformation conditions leading to initiation of cracks.

The quantitative tests for evaluation of the sensitivity to hot cracking include the Bollenrath test [5], where the crack inducing deformation of the weld is adjusted by adjusting the distance between the clamps; Bauman MSTU composite sheet test [5], where the criterion is a minimum width of a sheet at which a crack is not formed; Bauman MSTU test for tubular specimens [5], i.e. length of a region from the tube edge to an insert, at which there are no cracks; IMET (Baikov Institute of Metallurgy and Materials Science) test for a thin-sheet material [5], i.e. maximum length of the weld to notch, at which there are no cracks; MSTU-LTP test [4], i.e. width of a plate at which there are no cracks; Lehigh test [7], maximum depth of slots at which there are no cracks; and U.S. Naval Research Laboratory test [7] with a keyhole slot, i.e. distance from the hole to the weld pool at the moment of crack initiation, or length of a crack. In turn, as a criterion for evaluation of the sensitivity to hot cracking the quantitative tests use design parameters of a joint, which provide its rigidity and serve as a comparative criterion that is proportional to the weld deformation rate [4].

The methods for quantitative evaluation of hot crack resistance of metal with forced deformation of a welded joint include the LTP-1-6 test [8], Ates and Frederiks, IMET-2, Blanshet and Murex tests [5], i.e. critical strain rate $V_{\rm cr}$ leading to crack formation; MSTU test [5], i.e. critical angular strain rate ω leading to crack formation; PVR test [9], Varestraint-Test and TransVarestraint-Test [10], and strain-to-fracture test [11], i.e. critical strain $\varepsilon_{\rm cr}$ leading to crack formation.

It can be assumed on the basis of the above criteria that the main cracking condition of both technological tests and quantitative test methods for determination of hot crack resistance of metal with forced deformation is achievement of a critical value of $\varepsilon_{\rm cr}$ within a certain temperature range in the crack formation region, which, in opinion of the authors of [2, 3], is related to degradation of metal.

Consider the methods for evaluation of cold crack resistance of steels in welding by using the same scheme: cruciform test specimen [4] — presence or absence of cracks; Tekken test specimen [4] — critical cooling rate leading to initiation of crack; circular-deposit test specimens, Cranfield and TsNIIMash [4] — critical quantity of shrinkage beads causing crack; Lehigh test specimen [4] — maximal depth of slots at which there are no cracks; VMEI (Higher Electrical Engineering Institute in Varna), TsNIITS and «circular-patch» test specimens [4] — critical geometric size of a specimen causing its rigidity; LTP MSTU and IMET 4 test specimens [12] — critical stress value to time-to-fracture ratio in hydrogen-containing environment; TRC [12] — critical stress value, below which there is no crack under a load that is normal to or directed along the weld; and incubation period for crack initiation.

As seen from some of the above methods used to evaluate resistance of steels to cold cracking, in welding these evaluation criteria can be similar to those used to evaluate hot cracking:

- qualitative (presence/absence of cracks (yes/no));
- semi-quantitative (relative length of cracks, critical cooling rate, critical initial temperature, and critical quantity of shrinkage weld beads);
- quantitative (critical geometric size of a specimen causing its rigidity, minimal stress at which the cracks are formed, set of welding conditions under which a crack is not formed, and critical strain rate and value at which a crack is formed).

As a rule, the cold crack resistance tests are the delayed fracture evaluation methods. This means that time to crack formation may amount from several minutes to several days or more, depending on the effect of ambient stress and long-time process of diffusion of hydrogen into the zones with an increased stress. Presumably, the main cause of hydrogen-induced cracks is reaching the limiting local concentration of hydrogen due to the presence of strains and stresses of a critical level in regions of a welded joint at a

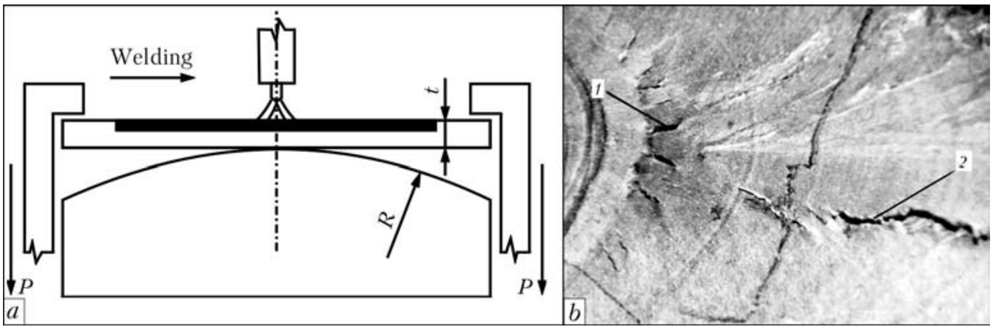

Figure 1. Scheme of dynamic deformation applied by using the Varestraint-Test method (*a*), and characteristic cracks formed in welding of alloys with high nickel content (*b*): *1* — BTR; *2* — DTR

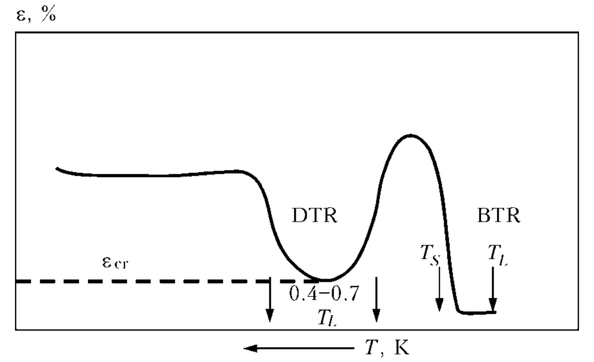

Figure 2. High-temperature ductility of metal with regions containing characteristic types of hot cracks

given temperature, i.e. under conditions of local degradation of metal leading to its embrittlement.

Consider the degradation processes in more detail by an example of high-alloy steels and heat-resistant nickel alloys from the standpoint of their technological strength in fusion arc welding, proceeding from the criterion of formation of hot cracks in the welded joint.

Figure 1 shows the scheme of the Varestraint-Test method and regions of formation of cracks in regulated bending of the welded joint during welding.

The experimental procedure provides for tungsten-electrode through-penetration welding of a plate using no backing. The initial part of the weld is made without deformation. The pneumatic drive that moves the clamps down is switched on at the time moment when the weld pool is located over the upper point of the mandrel. This process is not stopped at this moment, but is continued for some more time. As a result, metal of the weld pool and all zones both in the weld and HAZ is subjected to a preset deformation, which initiates hot cracking. Strain ε of the external layers of a specimen in bending is calculated from formula $\varepsilon = \frac{t}{2R} \cdot 100$ %, where t is the thickness of the plate welded, and R is the radius of the mandrel on which the specimen is bent [13].

The cracks initiated at high temperatures (Figure 2), which are close to the solidification temperature, form the so-called high-temperature brittle range (BTR [13]). It extends from liquidus temperature T_L to a region a bit lower than the solidus temperature (approximately by 100–150 °C). The low-temperature brittle range (DTR [13]) is in a temperature range of $(0.4–0.7)T_L$. Critical strain ε_{cr}, above which the cracks are formed, is approximately 0.1–1.5 % for different chrome-nickel steels.

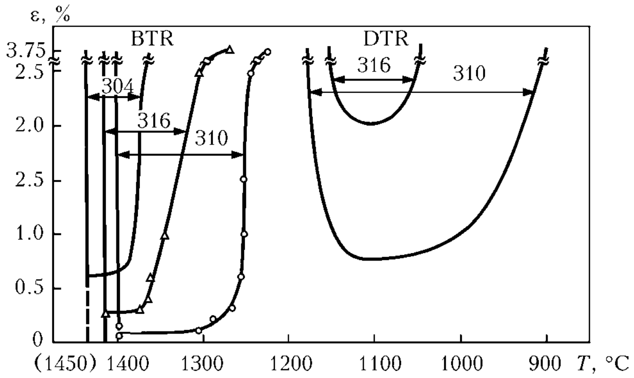

Figure 3. Brittle temperature ranges for welds on austenitic stainless steels of the 304, 310 and 316 types determined by the Varestraint-Test method

Experimental data on evaluation of crack-inducing temperature-deformation conditions are shown in Figures 3 and 4 for a number of welded joints on stainless steels, and for heat-resistant nickel alloys with polycrystalline and single-crystal structure. For instance, steel AISI 304 (analogue of domestic steel 12Kh18N9) is insensitive to cracking (Figure 3), steel AISI 316 (analogue of steel 10Kh17N13M2) has moderate sensitivity, and steel AISI 319 (analogue of steel 20Kh23N18) exhibits an increased sensitivity to cracking [13, 14]. In turn, polycrystalline and single-crystal nickel alloys with the γ′-phase content of 50 and 60 %, respectively, are characterised by low crack resistance.

The sensitivity to cracking has two fundamental points, which are worthy of notice.

The first point is a critical level of strain, ε_{cr}, above which macrocracks are formed in the weld and HAZ metal at certain temperatures. In our case, this characteristic is one of the weldability criteria, i.e. it is based on evaluation of the sensitivity to

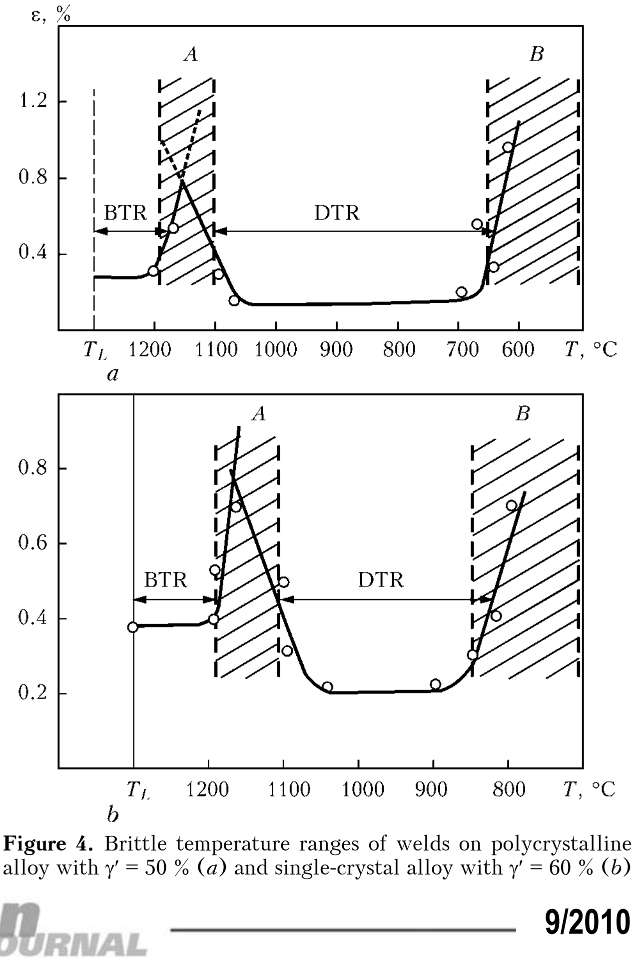

Figure 4. Brittle temperature ranges of welds on polycrystalline alloy with γ′ = 50 % (*a*) and single-crystal alloy with γ′ = 60 % (*b*)

Characteristics of brittle temperature ranges and critical stresses for cracking determined by TransVarestraint-Test method

Steel or alloy grade	BTR, °C	DTR, °C	ε_{cr}, %	
			BTR	DTR
304	1450–1420	–	0.75	–
316	1415–1375	1150–1050	0.25	2.00
310	1400–1300	1175–1000	0.10	0.75
Ni-based, γ' = 50 %, polycrystal	T_L–1190	1110–670	0.28	0.15
Ni-based, γ' = 60 %, single crystal	T_L–1190	1105–790	0.38	0.20

cracking. The values of ε_{cr} in BTR and DTR are given in the Table.

The lower the value of ε_{cr}, the higher is the sensitivity of material to hot cracking, or the lower is the safety factor for crack resistance.

The second point is the character of variations in the $\varepsilon_{cr} = f(T)$ curve. As a rule, the temperature curve of ductility has nominal values in the zones between BTR and DTR, as well as from the end of DTR to room temperature (Figure 4, *a*, *b*). The zones of nominal ductility are dashed and designated as *A* and *B*. Note that in both temperature ranges, i.e. BTR and DTR, where the crack resistance of the weld is much lower, a set of mechanical properties changes towards deterioration. That is, the degradation of metal takes place. This is evidenced by the course of the $\varepsilon = f(T)$ curve, angles of its inclination and width of the ductility-dip zone. The welding technology under such conditions can accelerate the degradation of metal by absolute values of the criterial properties, which characterise weldability of steel or alloy of a given chemical composition and production method. Therefore, the numerical indicator of weldability and its absolute value depend on the effect of the welding technology on a corresponding degradation of physical properties of metal, i.e. its sensitivity to cracking. In this case, this is a change of deformability with respect to the initial or stabilised state of a given material.

The causes of formation of cracks can possibly be explained proceeding from comparative analysis of the stress-strain state in the welded joints on high-nickel alloy JS-26, which is sensitive to cracking, and austenitic stainless steel 03Kh20N16AG6, which is resistant to cracking. The explanation was based on evaluation of weldability by the degree of degradation. Current values of longitudinal stresses and plastic strains were determined depending on the temperature at the point located at a distance of 0.5 mm from the fusion line both on the branch of heating to T_{max} and on the branch of cooling to 20° by using experimental data and calculation methods. It follows from the calculation data shown in Figure 5 that the level of tensile longitudinal stresses in nickel alloy reaches about 920 MPa, this corresponding to the yield stress in the ductility-dip temperature range, while the value of plastic strain is approximately 1.75 %, which is almost an order of magnitude higher than $\varepsilon'_{cr} \approx 0.15$ %. Therefore, conditions for intensive degradation of metal were thus created, which showed up in formation of cracks in DTR. The level of stresses in austenitic steel was also close to the yield stress and amounted to 390 MPa, and that of plastic strain was about 0.5 % at $\varepsilon'_{cr} \approx 4$ %. As the degradation of metal does not reach the level that causes cracking, the steel belongs to those that are easy to weld [15].

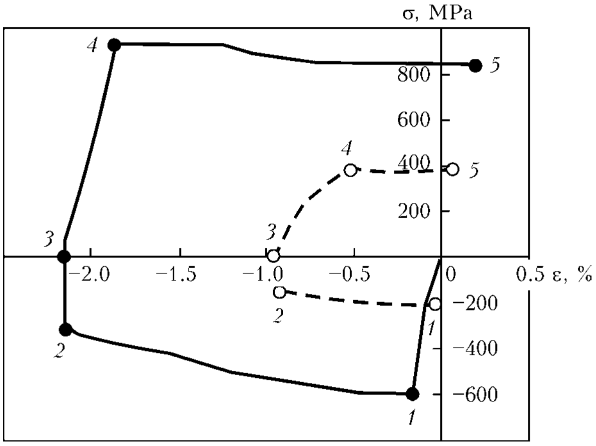

Figure 5. Calculated evolution of stresses and strains in welding of nickel alloy and austenitic steel: points *0–2* — heating, *2–5* — cooling; solid curve — nickel alloy JS-26, dashed curve — steel Kh20N16AG6

Therefore, this proves correlation between the technological strength and weldability, and that they can be evaluated by the degree of degradation of metal. In this case they can be evaluated from strain ε, which, when it reaches a critical value, causes cracking of a welded joint at certain temperatures that are characteristic of a welding cycle.

CONCLUSIONS

1. The above methods for determination of technological strength have different criteria. They can be used to investigate a wide range of materials joined and welding technologies. Deterioration of crack resistance and sensitivity to delayed fracture and embrittlement of material up to formation of discontinuities (micro- and macrocracks), which is indicative of occurrence of the processes causing a negative change in properties of the material, are the criteria

that are generally used to evaluate the technological strength (weldability).

2. Any deterioration of properties occurring with time under certain conditions of thermal-load and additional effects on metal, which are characteristic of welding, leads to a limiting state of metal, which causes formation of discontinuities of an inter- or transcrystalline character and degradation.

3. The degradation of properties of metal of the joint should be regarded as a universal criterion for evaluation of the technological strength and, hence, weldability.

1. Yushchenko, K.A., Derlomenko, V.V. (2005) Analysis of modern views on weldability. *The Paton Welding J.*, **1**, 5–9.
2. Yushchenko, K.A., Derlomenko, V.V. (2005) Materials weldability criteria. *Ibid.*, **8**, 68–70.
3. Yushchenko, K.A., Derlomenko, V.V. (2006) Weldability and changes in physical-mechanical properties of welded joints. *Fiziko-Khimich. Mekhanika Materialiv*, **2**, 89–93.
4. (1979) *Welding in machine-building*: Refer. Book. Vol. 3. Moscow: Mashinostroenie.
5. Shorshorov, M.Kh., Erokhin, A.A., Chernyshova, T.A. et al. (1973) *Hot cracks in welding of heat-resistant alloys*. Moscow: Mashinostroenie.
6. (1991) *Welding and materials to be welded*. Vol. 1: Weldability of materials: Refer. Book. Ed. by E.L. Makarov. Moscow: Metallurgiya.
7. Stout, R.D., Dorville, W.D. (1978) *Weldability of steels*. New York: Welding Res. Council.
8. Hrivnak, I. (1984) *Weldability of steels*. Ed. by E.L. Makarov. Moscow: Mashinostroenie.
9. Wilken, K. (1998) Investigation to compare hot cracking tests of externally loaded specimen. *IIW Doc. IX-1923–98*.
10. Savage, W.F., Zuntic, C.D. (1965) The Varestraint Test. *Welding J.*, 44(**10**), 433–442.
11. Nissley, N.E., Lippold, J.C. (2003) Development of the strain-to-fracture test for evaluating ductility-dip cracking in austenitic alloys. *Ibid.*, 82(**12**), 355–364.
12. Shorshorov, M.Kh., Chernyshova, T.A., Krasovsky, A.I. (1972) *Weldability tests of metals*. Moscow: Metallurgiya.
13. Kamoi, K., Machora, Y., Ohmosy, Y. (1986) Effect of stacking fault precipitation on hot deformation of austenitic stainless steel. *Transact. of ISIY*, 26(**2**), 159–166.
14. Yushchenko, K.A., Savchenko, V.S., Chervyakov, N.O. et al. (2010) Probable mechanism of cracking of stable-austenitic welds caused by oxygen segregation. *The Paton Welding J.*, **5**, 5–9.
15. Savchenko, V.S., Yushchenko, K.A., Zvjagintseva, A.V. et al. (2007) Investigation of structure and crack formation in welded joints of single crystal Ni-base alloys. *Welding in the World*, 51(**11/12**), 76–81.

TREATMENT OF THE SURFACE OF ALUMINIUM-MATRIX COMPOSITE MATERIALS BY CONCENTRATED ENERGY SOURCES

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Studied was the possibility of modifying surface layers of antifriction aluminium alloy AK9 and aluminium-matrix composite materials reinforced with particles of silicon carbide SiC and aluminium oxide Al_2O_3 in melting of surfaces with arc discharge in magnetic field, as well as with pulsed laser beam. It is shown that surface melting is accompanied by substantial dispersion of the initial surface layer structure. Samples after treatment are characterized by mechanical and tribological properties that are superior to those of the initial material.

Keywords: *arc surface melting, pulsed laser radiation, reinforced composite materials, magnetic field, modified surfaces*

At present designers are showing interest in aluminium-matrix composite materials (CM) reinforced by refractory ceramic particles. Above-mentioned CM are characterized by high wear resistance and tribological properties, making them promising for application in tribounits [1, 2]. A highly important direction of further work is producing wear-resistant antifriction coatings from these CM on parts operating under extreme conditions. Studies [3–8] show the possibility of producing wear-resistant coatings from such materials by argon-arc surfacing with application of filler rods, the deposited coatings being characterized by service properties close to those of cast CM of the same composition. There is a further possibility of improvement of service properties of surface layer of initial CM and deposited coatings by modifying their structure, as a change of dimensions of structural elements markedly influences the part wear resistance [9].

In [10, 11] it is proposed to apply microplasma discharges, as well as electron beam and laser radiation for modifying the surface. However, such methods of CM surface treatment are not always cost-effective, because of the low treatment speed, as well as the need for application of complex and expensive equipment. In addition, microplasma treatment in vacuum chambers is related to limitations in product dimensions, and in laser treatment it is also necessary to take into account the reflecting properties of the treated material. A more cost-effective and flexible process of CM surface treatment is arc surface melting with magnetic field impact on the arc and molten pool, allowing high-quality dense surface layers of homogeneous composition to be produced [12].

This work presents the results of investigation of the possibilities of arc surface melting in a magnetic