

Some Approaches to the Evaluation of Permissible Technological Defects in Welds of Equipment and Pippings for NPP with Water and Fast Reactors

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ABSTRACT

The investigation of the effect of production welding defects on the strength of welded joints manufactured from Cr-Ni austenitic, low carbon and low alloyed ferritic-perlitic and perlitic steels has been performed. Tests have been carried out under static, thermo-cyclic and low cycle isothermal loadings simulating PWR and FBR equipment and piping operation. It has been shown that defects effect is maximal by cyclic loading when they decrease weldments strength and lifetime (the degree of flaws effect depends on loading type). Strain concentration, produced in loaded weld metal by defects is shown to depend on defect type, geometric, physical and mechanical factors. The objective strain concentration is the effective strain concentration factor K_{ϵ_f} , determined with the use of experimental results. For isothermal low cycle loading (for example, pressure vessel operation condition at 350°C) it is possible to calculate the strain concentration factor K_{ϵ} (its value correlates with K_{ϵ_f} values for volume flaws). An evaluation procedure of welding defects acceptance basing on cyclic strength and lifetime calculation has been proposed.

1 INTRODUCTION

Welding is one of the main production processes by NPP equipment and piping manufacture. The service life of these structure components are in considerable degree determined by welds quality. High requirements to NPP components service life and financial reasons make it necessary to have a clear idea of the defects effect on weldments service life in operation conditions. The statistical analysis of welded NPP components defects demonstrates the volume defects to meet more often (they are slag inclusions, pores, tungsten inclusions found by argon-shielded welding). Plane defects are met more seldom (they are lack of fusion, cracks). The defect acceptance standards consider volume defects to be restrictively permitted. The acceptable defect size is determined based on welded joint thickness

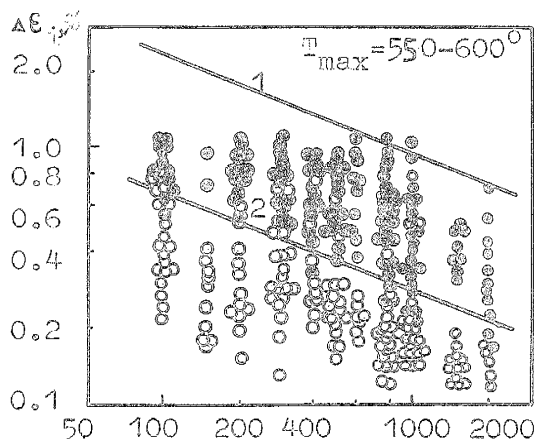
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and weldment category considering welded structure operation conditions and possible repair after assembling or during service. It should be noted that the current defect acceptance standards for NPP structures are very strict and based on the abilities of non-destructive inspection methods and production processings. Plane defects are not to accept. The defected structure critical condition is to evaluate on base of fatigue fracture initiation (microcracks appearance by cyclic loading) and brittle fracture initiation (for thick-walled pressure vessels made from low alloyed and low carbon steels). In NPP equipment with VVER reactor (thick-walled pressure vessels) in heavy loaded zones and in locations of strain concentration, low cycle isothermal loading is realized. By the operation of NPP equipment with FBR in transition regimes a rapid liquid metal coolant moving is possible which results in thermal stresses occurrence in structure components. Therefore, it is a more actual problem for such structures to study production defects influence on weldments fatigue strength by thermal and cyclic loading. The thermal and cyclic loading effect on reactor components in transition regimes is complicated by the prolonged high temperature (up to 600°C) attack in the period of steady reactor operation (90% of the whole lifetime) which results in static damage accumulation. In this connection, parallel with the study of defects influence on weld metal fatigue fracture resistance, it appears to be necessary to determine their effect on weld metal strength by static loading.

2 INVESTIGATED MATERIALS

Tests have been carried out on welded joints of austenitic Cr-Ni steel of 09X18H9 type, produced by manual electric arc and argon-shielded arc welding processes (for FBR components) and on weldments of 22K, 15X2MFA and 08X18H10T steels manufactured by manual, electric arc and automatic submerged arc welding (for PWR components).

3 TEST RESULTS AND ANALYSIS



Tests under short-term and long-term loadings have been performed on specimens manufactured from Cr-Ni 18-9 steel weldments produced by manual electric arc welding with the electrodes of A-1 grade and by argon-shielded arc welding. The specimens con-

Fig.1. Slag inclusions effect on weld metal thermal fatigue resistance:
 1 - without defects,
 2 - with slag inclusions(2-3mm).

tained defects (pores, slag and tungsten inclusions). By short-term tension tests at 500, 600, 650°C a small decrease of weld metal temporary resistance (R_m^T) was found, it appeared to be almost proportional to weld metal area reduction in specimen cross section at the expense of located there defects (Fig. 1). The R_m^T value was practically independent on defect type. In opposite to R_m^T the defected weld metal plastic characteristics were sufficiently decreased. For example, by 10% porosity in the defected specimen cross section the value of elongation and reduction of area are equal to 16- and 45% respectively as compared with the values of 27 and 54% for the undefected specimen. Specimens test results at 600°C under prolonged static loading showed the welding defects to influence on material creep rupture. So, by 3% and 10% porosity as related to specimen cross section the weldment creep rupture (after 1000 hours) was decreased by 12% and 20%, respectively. A higher degree of creep rupture decrease as compared with R_m^T is caused by the increased weld metal sensibility to stress concentration on account of its embrittlement by strain aging. To perform thermal-cyclic tests cylindrical specimens (diameter 20 and 40mm) were manufactured from Cr-Ni austenitic steel weldments, containing defects of various types and sizes, which were located in the middle zone of the specimen.

The specimens were loaded with the following thermal-cyclic mode: $500 \pm 200^\circ\text{C}$, $600 \pm 200^\circ\text{C}$, $550 \pm 20^\circ\text{C}$, $600 \pm 20^\circ\text{C}$ at rapid or slow heating and sharp cooling in various media. The number of loading cycles varied from 50 to 2000. The cyclic strain range at various welded specimen section points is determined for each loading type by finite element method. The tested specimens were cut so as the cutting plane was passing through defects (the defects location was determined by X-ray method). The microsection metallographic specimens were manufactured to determine the appearance and propagation of thermal fatigue cracks from defects. A crack of 0.1mm length was taken as a failure criterium. The obtained results were plotted as a function $\Delta \epsilon_i - N$ (cyclic strain range - the cycles to failure). The mathematical data processing with discriminant analysis showing the failure presence ($l_{cr} \geq 0.1\text{mm}$) or absence ($l_{cr} < 0.1\text{mm}$) per-

mits to obtain the calculation curve of discriminant function, separating two groups of results. In such a way the thermal fatigue curves were constructed for weld metal containing defects - pores, slag and tungsten inclusions of different sizes. Figure 1 illustrates the thermal fatigue curve for weld

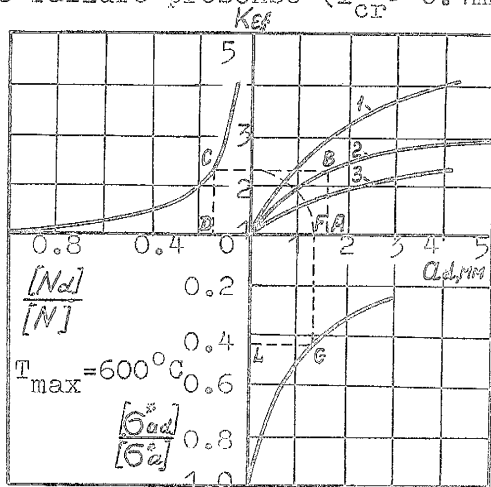
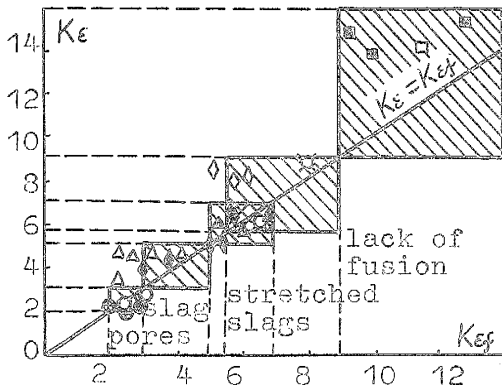


Fig. 2. Nomograms for estimation of production welding defects effect on welded joints strength.

metal containing slag inclusions and for comparison - for weld metal without defects. The influence of defects on weld metal thermal fatigue resistance may be characterized by the effective strain concentration, its value (by a given number of loading cycles) being determined with the relation of cyclic strain ranges for weld metal containing defects or without defects. ($K_{\epsilon f} = \Delta \epsilon_i / \Delta \epsilon_{id}$). For example, for slag inclusion size of 2.5mm the value $K_{\epsilon f} = 3.5$ (Fig.1), the number of loading cycles - 10^7 . Based on these results the curves $K_{\epsilon f}$ versus a_0 (defect size) may be constructed for slag inclusions, pores and tungsten inclusions (Fig.2). They show the strain concentration produced by defects to be dependent on defect type; slag inclusions of various form (from globular to stretched, acute-angled) appeared to be most dangerous. As for tungsten inclusions their effect is not so dependent on their forms, because a strong inclusion/matrix cohesion has formed, and the maximal weld metal strain has taken place not at the boundary with defect, but at some distance from it.

In general, stress and strain concentrations at welding defects are determined by geometric, physical and mechanical factors. Besides the evident effects of geometric factors and the above-mentioned strong cohesion at the defect/matrix boundary, the correlation between the modules of elasticity of the defect and matrix materials is also important. In the case of thermocyclic loading we should take into consideration the difference in weld metal and defects thermal conductivity causing the distorting of temperature field and the appearance of zones with higher stress and strain concentration in the vicinity of defects (Balandin et al. 1986). Thus, stress and strain concentrations produced by defects depend on various factors. The most appropriate criterium, taking into account the effect of numerous factors, appears to be the effective stress and strain concentration factor. Using the values of $K_{\epsilon f}$ for various defects and the characteristics of weld metal long-term strength and ductility we may calculate the long-term cyclic strength of weld metal with detected by inspection defects. The calculation method is given in PNAE G7-002-86. The calculation results may be presented as nomograms permitting to evaluate the welded joints strength and lifetime decrease due to the effect of detected effects (Fig.2).

The acceptance evaluation of production defects in welded joints

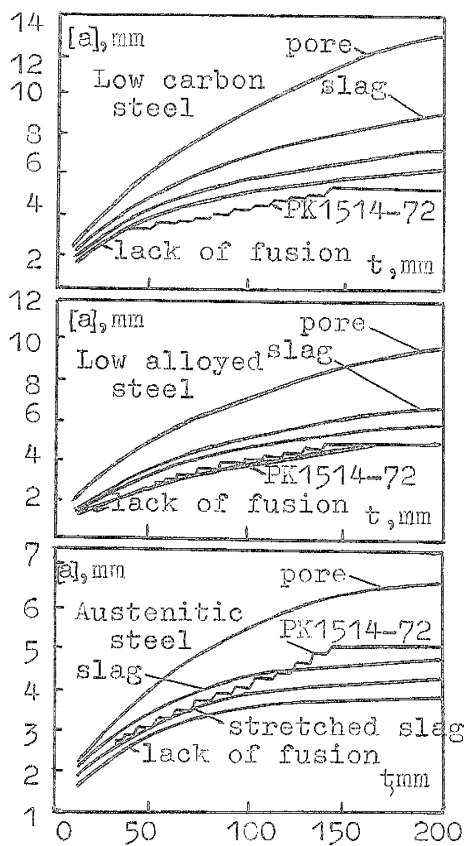


of thick-walled components of NPP with VVER reactor is made with regard for their effect on weldments low cycle fatigue resistance. It should be taken into consideration that cyclic changes of inner pressure and temperature are most dangerous.

Fig.3. The comparison of effective strain concentration factors K (with calculated K values) for various defects.

The possible brittle fracture or leakage occurrence may be considered to be the critical pressure vessel condition. Therefore the maximal acceptable calculated defect size a_0 must be less than a_{cr}/n_{cr} (where a_{cr} - the critical defect size of a crack type, n_{cr} - safety margin), it must exclude the brittle fracture initiation under any possible operation loading during the whole planned period of structure operation. The accepted defects in structure should not exceed the value of a_p . It may be expressed analytically as $a_0 + \Delta a(N, \Delta K, C, m) \leq a_p$,

where a_0 - initial defect size; Δa - defect grow increase; N - number of loading cycles; ΔK - stress intensity factor; C, m - parameters, characterizing material fatigue crack growth resistance (the constants of Paris equation, $da/dN = C(\Delta K)^m$). To calculate the cyclic strength of pressure vessel weldments based on PNAE G7-002-86, we should determine the structure critical condition by the moment of microcrack initiation. An acceptable defect size is to determine with the regard for the effective strain concentration factor K_{ϵ} (which is experimentally defined for defects of various types and sizes). Besides, as by low cycle isothermal loading the geometric factor appears to be determinant, we may introduce the calculation parameter - strain concentration coefficient, which characterizes strain concentration at defect tip and differentiates defects according to their form and size effects at the moment of fatigue crack initiation.



The K_{ϵ} factor is determined (in complex stressed and strained conditions by loading process in defect zone) as the relation of maximal values of strain intensity in the vicinity of defects or apart from it. Defects are simulated in the following manner: sphere $\varnothing 10$ mm (the initiation of a gaseous pore or rounded slag inclusion); ellipsoid of revolution with axes relation 10:6 and rotation radius $\rho = 1.8$ mm (stretched slag inclusion); ellipsoid of revolution with axes relation 10:2, $\rho = 0.2$ mm; thin disc with axes relation 10:0.2, imitating of slag film with $\rho \leq 0.01$ mm (Karzov et al. 1982). The evaluation of stressed-strained condition in defect zone by elastic-plastic loading was performed by finite element method. The comparison of experimental and calculated results shows a good correlation for single defects (Fig.3). For more dangerous defects (lack of fusion, Fig.4. The size dependence of single acceptable compact defects of various geometric configuration on welded components thickness.

chain of slag inclusions) the calculated K_{ϵ} values appeared to be higher than experimental K_{ϵ} values. Basing on strain criterion of fatigue damage initiation and strain concentration factors K_{ϵ} , it is possible to determine the amplitude of local strains in various configurations defects tips which permits to calculate the relative service life before the initiation of fatigue cracks N_{ϵ}/N with the use of steel weld metal low cycle fatigue curves. If the defects acceptance is estimated with the regard for crack initiation and propagation stage before reaching the dangerous for a structure a_D value, the curves of accepted single defect sizes versus welded components thickness t may be constructed. Figure 4 illustrates such relations for welded joints of low carbon ferritic-perlitic, low alloyed perlitic and Cr-Ni austenitic steels. Here "The Inspection Regulations" PK1514-72 is also given, which specify the permissible defect sizes in the weldments of NPP with VVER reactor. An essential difference in acceptable sizes of defects of various types (especially pores and slag inclusions) is observed. The sizes of acceptable defects of one type but of various materials are also differed. The requirements of PK1514-72 Regulations are somewhat conservative for pores and compact slag inclusions, but agrees with the requirements providing components necessary cyclic strength as regarding for actu-angled slags.

CONCLUSIONS

1. By short-term static loading welding defects decrease weldments strength approximately proportionally with the detection level in weld section. By long-term static loading of Cr-Ni steel weldments an increased defects influence is observed.
2. All welding defects essentially decrease weldments strength by cyclic loading, the decreasing depends on defects and cyclic loading types.
3. The defect acceptance evaluation procedures and acceptance criteria for NPP welded components should be based on calculated estimation of cyclic strength of welded joints with defects of various types and sizes. In calculations basing on strain criteria of fatigue damage the experimental K_{ϵ} values and weld metal creep rupture strength and ductility should be taken into consideration (if it is necessary to consider temporal processes).

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