The Effect of Metallurgical Factors on Crack Resistance of Pressure-Vessel Materials

V. T. Troshchenko, V. V. Pokrovsky, V. G. Kaplunenko,
G. P. Karzov, V. T. Timofeev, Yu. G. Dragunov
Institute for Problems of Strength, Academy of Sciences of the UkrSSR, Kiev, USSR

ABSTRACT

The paper deals with the investigation into static and cyclic crack growth resistance of pressure-vessel materials which are obtained by different melting and welding techniques. It is established that metallurgical factors affect the cyclic crack growth resistance in the structure-sensitive near-threshold and high-amplitude regions and reveal no effect in the structure-sensitive Paris region. In general the weld-metal crack growth resistance is found to be higher than that of the base-metal.

INTRODUCTION

Within the alternative practices and materials applied for manufacturing the responsible pressure vessels it is advantageous to use the materials which as much as possible meet the stringent safety requirements for the pressure-vessel operation within the designed lifetime. Basing on the fracture mechanics approaches the choice of the pressure-vessel materials is stipulated by the requirement for obtaining the reliable data on their crack growth resistance characteristics with the account taken of the various factors and mainly the manufacturing effects.

The most reliable crack growth resistance evidences for pressure-vessel materials are obtained in real-thickness specimen testing. It is of the upmost importance to have this information with respect to welded joints which manifest themselves nonuniform behaviour over the thickness compared to the base-metal. The non-uniformity of the mechanical behaviour, chemical composition and structure of the actual welded joints are certain to be manifested in real-thickness specimens testing.

With regard of the abovementioned the objective of the paper presented is to study the static and cyclic crack growth resistance characteristics, pressure-vessel materials of the various heat-treatment with different content of alloying elements and deleterious impurities as well as those characteristics for the welded joint materials which are effected by various welding techniques with the usage of different weld-metals.

TESTING PROCEDURE AND THE MATERIALS STUDIED

The test compact-tension 150 mm-thickness specimens were made of the base- and weld-metal whose chemical composition and mechanical properties are listed in the Table. Here the 15Kh2MFA steel, the 15Kh2NMFA steel, the Sv-10KhMFT weld-metal characterized by the higher content of copper and phosphorus impurities, in service enhance material embrittlement and are termed "contaminated". The 15Kh2MFA steel, the 15 Kh2NMFAA steel and the Sv-10KhMFTU weld-metal are termed "uncontaminated".

In weld-metal specimens the notch coincided with the weld centerline in so far that in testing the fatigue crack propagation occurred along the weld length. It is the zone adjacent to the weld centerline which is the weakest in the weld joint due to the conditions arising in the single-run electroslag welding when the zone is characterized by the maximum contamination by liquation impurities. For the automatic multi-run welding under the flux layer with the notch oriented along the weld centreline it is possible to take the account of the prior local nonuniformity of the mechanical properties and chemical composition over the weld height. Under those conditions the front of the propagating crack will involve the region of the weld root effected by the usage of the lower-alloying weld materials.

All specimens tests were conducted at the temperature 293 K in compliance with the recommended practices. The loading frequency constituted 7... 9 Hz and the stress ratio 0.1.

EXPERIMENTAL RESULTS AND DISCUSSION

The results obtained in present study are listed in the Table as well as shown in Fig.1 as the dependences of the rate of the fatigue crack propagation (FCP) da/dN on the maximum value in a cycle of the stress intensity factor (SIF) K_{Imax} .

Here in Fig.1a the above dependences are shown for the metals and welded joints based on the 15Kh2MFA steel while Fig.1b describes those for the 15 Kh2NMFA steel. The Table does not present the mean values of the static and cyclic fracture toughness (K_{Ic} and K_{fc} , respectively) but the values obtained for each specimen on study.

As is seen from Fig.1 and the Table the metallurgical factors have no appreciable effect on the FCG rate in the structure-insensitive Paris region but unambiguously affect the FCG regularities in the structure-dependent near-threshold and high-amplitude regions.

Thus in the near-threshold region the "contaminated" Sv-10KhMFTU weld is characterized by the much lower values of the threshold stress intensity factor K_{th} as well as much higher FCG rate compared to the "uncontaminated" Sv-10KhMFTU weld. On the other hand the "uncontaminated" 15Kh2MFA-A steel shows a higher FCG rate while the value K_{th} being lower compared to the "contaminated" 15Kh2MFA steel. For the "uncontaminated" 15Kh2NMFA-A and the "contaminated" 15Kh2NMFA steel in the near-threshold region the FCG rate and the value of K_{th} are practically equal. In the near-threshold region the lowest crack growth resistance is pertinent to both the materials on the basis of the 15Kh2MFA and the 15Kh2NMFA steel in the welded joint effected by electroslag welding and having the most coarse grain structure (Fig.1a - Sv-13Kh2MFA, Fig. 1b - Sv-16Kh2NMFA).

The specific feature of the fatigue crack propagation in the welded joints made by multi-run welding (Sv-10KhMFT, Sv-10KhMFTU, Sv-08KhGNMTA) is that this propagation is affected by the residual stresses whose values are close to the nominal ones generated in the near-threshold region. These stresses with the variable sign and the absolute value over the specimen thickness cause the significant difference of the local effective SIF compared to the calculated K_{Imax} what results in the respective local reduction or increase of the FCG rate. This is testified by the crack front which in the near-threshold region has the shape close to the diagram of the residual stresses. It is of importance that for the middle- and high-amplitude regions where the nominal stresses are sufficiently lower compared to the residual ones the latter have no notable effect on the FCG rate. In general, in the near-threshold region the weld-metals show lower crack growth resistance compared to the other metals. And here the FCG regularities are signicantly affected by the cluster of the following main factors due to the metallurgical effects, i.e. the grain sizes and consequently the length of their boundaries where the fatigue crack propagates; the presence and value of the residual stresses; the dependence of the oxide film formation on the chemical composition which causes the prior crack closure.

The analysis of the experimental data listed in the Table shows that the base-metal fracture toughness characteristics K_{Ic} and K_{fc} obtained for various specimens as well as those obtained for different types of loading (static and cyclic) are close, while the above characteristics for the weld-metals could differ more than 2-fold.

The difference of the fracture toughness characteristics obtained for various specimens is apparently due to the sufficient stress-state nonuniformity over the section of the weld, the chemical composition and structure variation which are pertinent to the materials of the welded joints of a large cross-section and which are caused by a number of factors, i.e. the thermoplastic effect on the metal arising in welding, the metal contamination by the deleterious impurities of copper and phosphorus due to the welding process, heat treatment after welding and others. Since the material fracture toughness is largely ascribed to the crack initiation mechanism which in turn is highly dependent on the stress-state, structure and the material mechanical properties, the fracture toughness of this material welded joint will be determined by the material state involving its properties, structure and the stress-state in the specimen part along which the boundary of the onset crack passes. This was substanciated by the fact of the multiple crack onset in the same specimen, i.e. after the crack onset which passes the zone with the lower fracture toughness it arrests in the zone with the higher fracture toughness, while the next crack onset occurs only after the load increase.

In general, metals of the welded joints show the much lower fracture toughness characteristics compared to the base-metal and in view of this the material behaviour will greatly affect the limiting state of the pressure vessel. Here for the welding techniques on study, electroslag welding is characterized by the metal welds with the lowest fracture toughness.

CONCLUSION

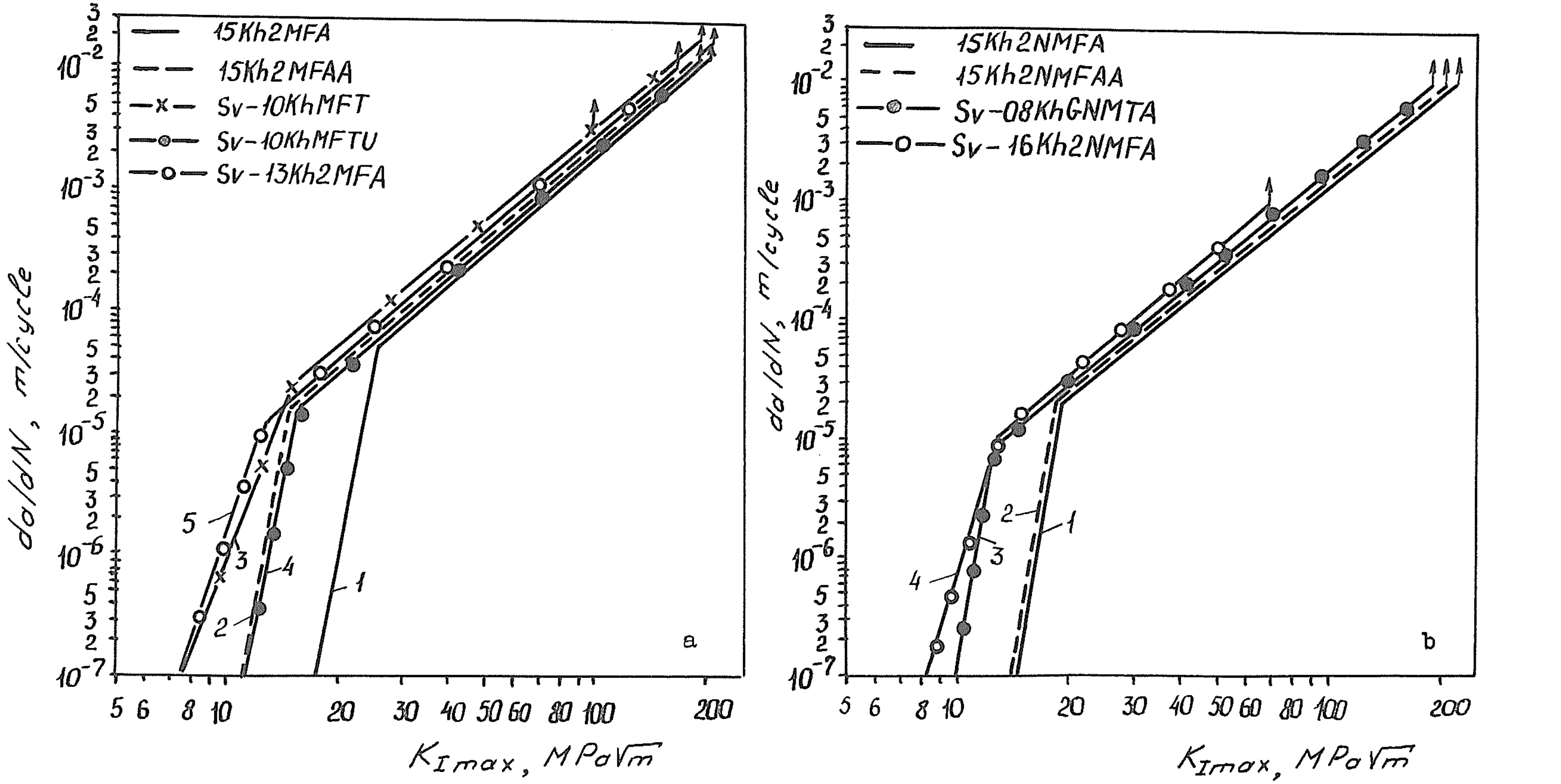
1. The pressure vessel materials cyclic crack growth resistance is highly affected by the material metallurgical features in the near-threshold and high-amplitude regions, but they have no effect in the middle-amplitude Paris region. Here the contri-

bution of the structure, nonuniformity of mechanical properties and the stress state are the most pronounced.

2. On the whole the weld-metals as compared to base ones show a significantly lower crack growth resistance and this characteristic will have an appreciable influence in assessing the limiting state of a pressure vessel. In this study the welded joints made by the electroslag welding showed the lowest crack growth resistance.

TABLE

Material	Welding technique	Content: Cu and P	Material properties σ_Y, MPa	σ_B, MPa	δ,%	ψ,%	Crack growth resistance characteristics K_{th}, MPa$\sqrt{m}$	K_{Jc}, MPa$\sqrt{m}$	K_{Ic}, MPa$\sqrt{m}$
15Kh2MFA steel "contaminated"		0.16Cu 0.014P	584	700	21.0	74.6	17.5	184;187 183;185	198;215
15Kh2MFAA steel "uncontaminated"		0.05Cu 0.012P	554	650	19.8	77.4	11	187	144
Sv-10KhMFT weld-metal "contaminated"	automatic multirun welding	0.17Cu 0.039P	490	620	21.3	73.3	7.6	88;173	146
Sv-10KhMFTU weld-metal "uncontaminated"	autom. multirun welding	0.06Cu 0.010P	481	593	21.5	70.1	11.2	175	87;84
Sv-13Kh2MFT weld-metal	electroslag welding	0.14Cu 0.10P	545	640	19.6	72.8	7.3	151	73
15Kh2NMFA steel "contaminated"		0.16Cu 0.012P	583	707	19.6	69.5	14.6	217	282
15Kh2NMFAA steel "uncontaminated"		0.05Cu 0.009P	490	608	23.0	76.0	14.2	202	232
Sv-08KhGNMTA weld-metal	autom. multirun welding	0.10Cu 0.006P	593	687	22.1	75.1	9.0	189	139
Sv-16Kh2NMFA weld-metal	electroslag welding	0.025Cu 0.009P	579	684	22.1	75.1	8.2	71	163



15Kh2MFA
15Kh2MFAA
Sv-10KhMFT
Sv-10KhMFTU
Sv-13Kh2MFA
da/dN, m/cycle
K_{Imax}, MPa√m
a
15Kh2NMFA
15Kh2NMFAA
Sv-08KhGNMTA
Sv-16Kh2NMFA
b

Figure I