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Division I

Study of the HAZ metal of the RPV welded joints

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ABSTRACT

Present work performed within international collaboration project of Materials Aging Institute (MAI) dedicates to in depth investigation of heat-affected zone (HAZ) of VVER-1000 reactor pressure vessel (RPV) steels. The primary aim of the project is to study sensitivity of the HAZ of RPV steel to brittle fracture in three typical states for the reactor pressure vessel: as-manufactured (reference state), irradiated and thermally aged. Results obtained for the HAZ's in the reference state are summarized in the present publication. Hardness profiles across the weld metal, HAZ and base metal were measured and the values of the critical brittleness temperature ($T_к$) were determined. Microstructural investigations were performed by means of scanning electron microscopy and fractographic analyses. The study was performed on the samples extracted from two welded joints of the 15Kh2NiMnV-AA steel. The welded joints were manufactured according to the standard technological procedures accepted for VVER-1000 RPVs.

INTRODUCTION

Narrow layer of the shell adjacent to fusion line belongs to HAZ. Part of the shell metal adjacent to fusion line is heated during welding processes. The overheating results in microstructural changes in this zone of the shell metal and results in local deviation of mechanical properties. The overheating results in microstructural changes in this zone of the shell metal and results in local deviation of mechanical properties. It is commonly accepted that mechanical properties of HAZ metal are worse in comparison to the base metal (BM) properties [1÷3].

Surveillance specimens (SS) are established to monitor degradation of RPV materials during operation. SS includes the BM, weld metal (WM) and HAZ specimens [4÷7]. There is no openly available experimental data on the surveillance specimens tests manufactured from HAZ metal, which would allow concluding if HAZ metal represent the most critical to compare with BM and WM.

Evaluation of HAZ metal mechanical properties degradation is commonly performed by means of Charpy V-notched (CVN) specimens impact tests. HAZ width corresponds to ~ 3-5 mm from the WM-BM fusion line [9]. The size of the working part of CVN specimens used in tests of HAZ metal corresponds to 8×10 mm. It implies that during these tests the fracture surface of the tested specimen most probably may also contain BM and WM. This can explain ambiguity of experimental data obtained using CVN specimens corresponding to HAZ metal.

The discrepancy between the size of the specimens used and the width of the zone under studied has led to the fact that quite a large part of the of HAZ studies is carried out on metal with a simulated HAZ. The disadvantage of this method is that the correctness of the simulation used is always in question [8÷11].

In this work a methodology for the study of HAZ metal is developed, which provides for the search of a local zone of the welded joint with the maximum tendency to brittle fracture.

The article is devoted to:

- a description of the methodology developed by the authors for studying the local zones of the RPV metal, in particular the HAZ metal, which allows us determine correctly to the properties of the metal in this area;
- obtaining an answer to the question of whether the HAZ of RPV weld joints is critical from the point of view of brittle failure;
- identification of the reasons for the differences in the properties of the metal HAZ and BM.
- The methodology assumes identification of the most tendency to brittle fracture zone of the weld joint in the typical for RPV states: as-manufactured (the reference state), thermally aged, and irradiated.

This paper dedicates to experimental results, obtained for reference state.

1 MATERIALS AND METHODS

There are no standard methods for testing of local areas of RPV metal. The methodology specially developed for the study of the metal of the HAZ, consists of the following steps:

1. Measuring of hardness profiles across the WM and BM for revealing of the areas with significantly different properties (different hardness values) and assessment the size, of these zones;
2. Selection of the specimen type representative for evaluation of Tк value of RPV at the local volume of metal;
3. Testing specimens from each local area;
4. Microstructural study for understanding the reason of differences in $T_к$ values from each local area.

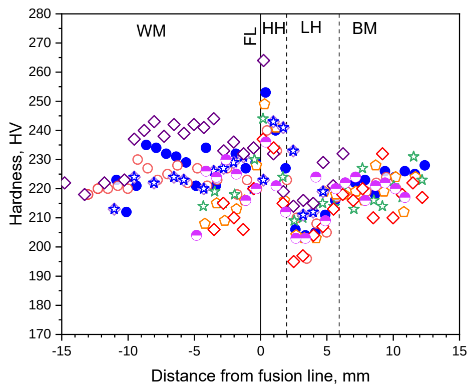
Two commercial welded joints marked as M and 50 of 15Kh2NiMnV-AA steel were selected for present study. Chemical compositions WM and BM, which are part of welded joints 50 and M, are indicated in Table 1.

Table 1 – Chemical compositions of the welded joints 50 and M.

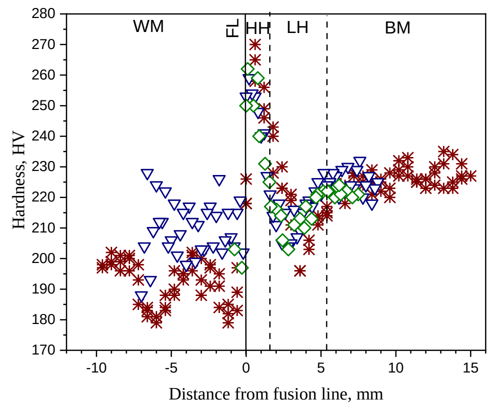
Welded joint	Metal	Chemical composition in wt. %									
		C	Si	Mn	P	S	Cu	Cr	Mo	Ni	V
50	BM	0.16	0.32	0.45	0.005	0.007	0.02	2.03	0.51	1.46	0.09
	WM	0.05	0.32	0.79	0.004	0.003	0.02	1.75	0.54	1.04	0.01
M	BM	0.17	0.29	0.47	0.009	0.010	0.05	2.25	0.51	1.34	0.09
	WM	0.07	0.25	0.75	0.006	0.014	0.07	1.78	0.65	1.80	0.02

In order to determine the size of zones with the properties changed relative to the base metal, the most local test method was used - hardness measurement. The hardness was measured by the Vickers method in all the zones of welded joints M and 50.

The hardness measurement results are shown in Figure 1.



a



b

Figure 1 – Results of hardness measurements of welded joints M (a) and 50 (b)
(Different designations refer to different specimens)
The negative coordinates in Figure 1 correspond to the distance from the fusion line (FL) towards WM

The regularity in the distribution of hardness depending on the distance from the fusion line was revealed. It corresponds with publications for other types of materials [1, 12-14]. The hardness distribution on the distance from the fusion line made it possible to split welded joint on distinguish 5 characteristic areas: weld metal (WM), fusion line (FL), high hardness (HH) area, low hardness (LH) area and base metal (BM).

The heat affected zone can be divided into 2 subzones: next to the fusion line, the subzone of high hardness (its width is 1-1.5 mm) is 15 - 35 units higher than the hardness of the base metal, then there is the subzone of low hardness 25 units lower than the hardness of the base metal. This area is 3-4 mm wide. The division by dotted lines into subzones is conditional, so there are transition areas.

Standard specimens cannot be used to assess the properties of such local areas. It was suggested to use mini-Charpy specimens with nominal dimensions of 5 × 5 × 27.5 mm (Figure 2).

Figure 2 –Standard full-size and mini-Charpy

The mini-Charpy specimens were manufactured to have the notch at locations where maximum (for the specimens of HH series) and minimum (for the LH specimens) hardness values were measured. Locations from which mini-Charpy specimens were cut out from the welded joint blanks is shown in Figure 3.

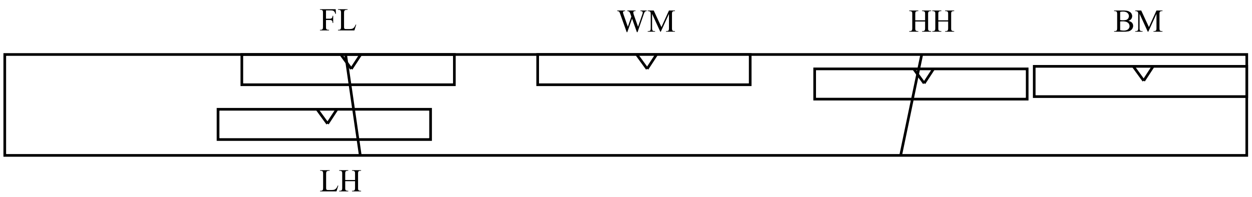


Figure 3 – Arrangement of mini-Charpy specimens in the welded joint blanks

The impact tests of the mini-Charpy specimens were carried out in a hot sell using an impact test machine RKP-150, which has a potential energy reserve of 86 J in accordance with GOST R 50.05.12-2018 [15]. For each zone, 12-13 samples were tested at different temperatures. Based on the test results, the value of the ductile-to-brittle transition temperature ($T_к$) was determined according to GOST R 50.05.12-2018.

2 RESULTS AND DISCUSSION

The data presented in Figure 4 show that each of the studied zones (WM, FL, LH, HH, BM) differs in $T_к$ values. The distribution of $T_к$ values for the studied areas is similar for the both welded joints.

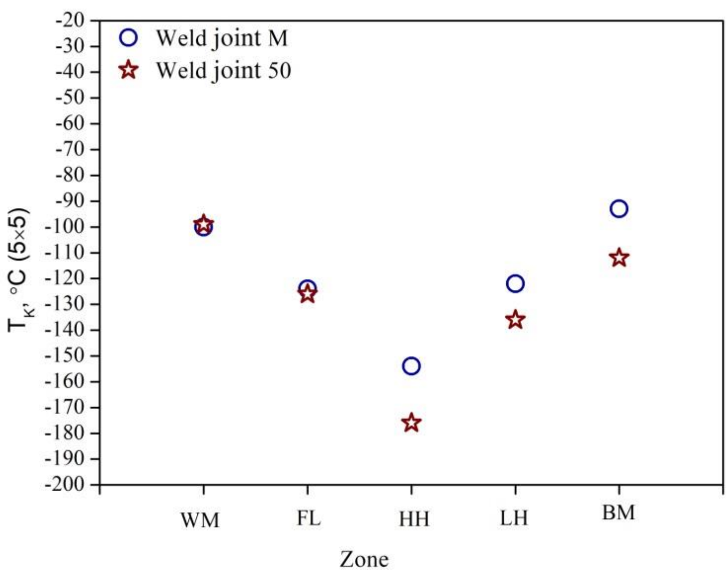


Figure 4 – Distribution of $T_к$ values in welded joints M and 50

The test results indicate that the maximum values of $T_к$ correspond to the WM and BM zones, while the minimum value of $T_к$ corresponds to the HH zone.

Typical microstructure observed on the lateral surface of the mini-Charpy specimen after chemical etching is presented in Figure 5.

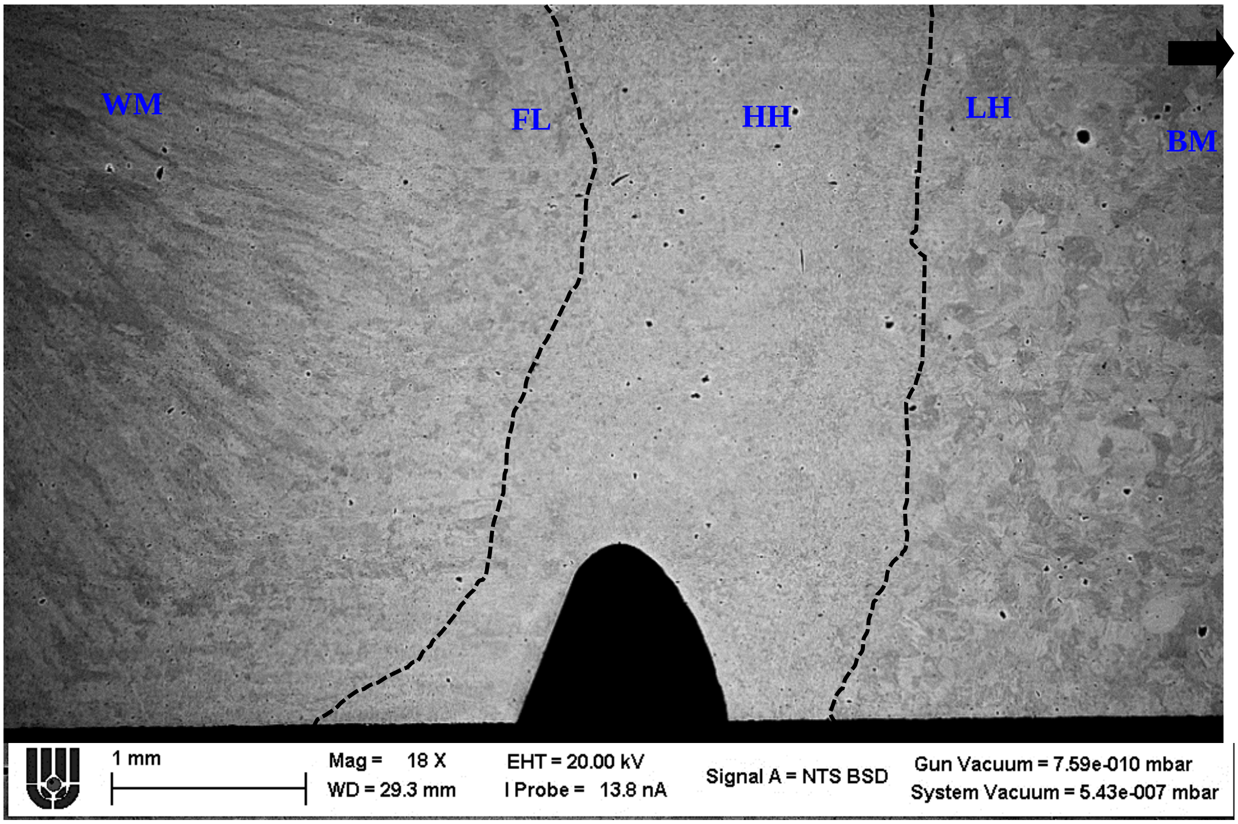


Figure 5– Typical image of microstructure of a mini-Charpy MH15 (weld M) specimen with a notch in the HH region. Dotted lines indicate the conditional division into HH and LH zones

The histograms of grain size distribution for various areas of welded joints M and 50 presented in Figure 6. The grain size was measured from about 600 to 1000-1100 grains depending location and the grain size itself. It was shown that the corresponding areas of these two welded joints have similar grain size distributions. While the BM and LH regions show the same grain size distributions, the distribution of grain sizes in the areas of the WM, FL and HH have significant differences in the range of grain sizes and differ from those in the BM and LH zones.

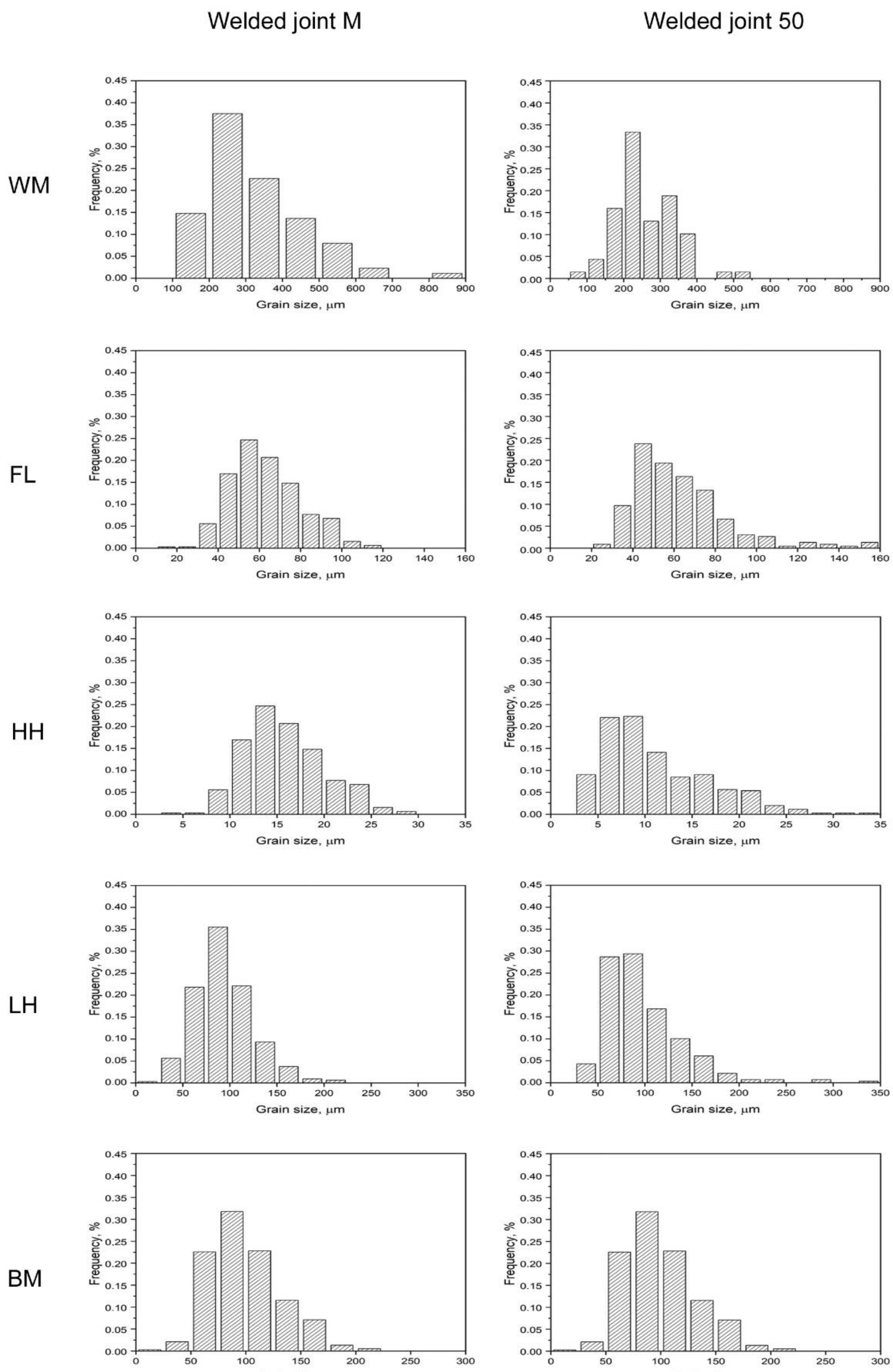


Figure 6 – The histograms of the grain size distribution of primary austenite grains for different zones of the welded joints M and 50

The minimum grain size is typical for the HH zone and the maximum - for the WM zone. In the LH and BM zones, the average grain size is practically the same. A correct comparison can be performed only for the same material (at list the same chemical composition), since the $T_к$ value depends on a number of factors including the chemical composition. It is possible to compare HH, BM and LH test results, because this zone has the same chemical composition. The minimum value of $T_к$ obtained in the HH zone can be associated with the formation of fine grains in a zone with a width of ~ 1.5-2.0 mm adjacent to the fusion boundary with a welded joint.

CONCLUSION

1. HAZ studies were carried out on two commercial welded joints, manufactured by the standard for VVER-1000 RPV technology.
2. The typical distribution of hardness depending on the distance from the fusion line was revealed. It was shown that the typical width of the HAZ region corresponds to 3-5 mm. The entire volume of the welded joint can be conventionally subdivided into 5 zones according to the results of hardness measurements:
   - –weld metal (WM);
   - –fusion line (FL);
   - –high hardness zone (HH);
   - –low hardness zone (LH);
   - –base metal (BM).
3. Significant differences in the T_K values for the identified zones are shown. The minimum value of the T_K, corresponds to the part of the HAZ (HH).
4. A much lower T_K values the HH zone compared to the BM (on 61-60ºC) is probably due to differences in the grain size (~15 mm for HH and ~100 mm for BM).
5. The T_K values of both areas of HAZ (HH and LH) are lower compare to BM and WM. It means HAZ is not the “weak link” of the welded joint in a received state.

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