Effect of Welding Thermal Cycle on Structural and Phase Weld Metal Transformations for Heat-Resistant Cr–Mo–V Steels

M. N. Timofeev*, G. P. Karzov, S. N. Galyatkin, and E. I. Mikhaleva
National Research Center Kurchatov Institute—Central Research Institute of Structural Materials Prometey, St. Petersburg, 191015 Russia
*e-mail: mail@crism.ru
Received October 26, 2015

Abstract—Results are presented for dilatometric and metallographic investigations and determination of microhardness for weld metal made of the materials for the automatic welding of VVER reactor vessels and oil hydrocracking reactor vessels. It is found that small differences in the content of alloying elements, such as nickel, chromium, molybdenum, and vanadium, cause differences in the structure of the weld metal before heat treatment.

Keywords: VVER reactor vessel, petrochemical reactor vessels, welding materials, dilatometry, weld metal microstructure
DOI: 10.1134/S2075113317060156

INTRODUCTION

The Russian and world experience in operation of water cooled water moderated nuclear reactors (VVER or PWR) for various purposes has shown the advantage of chromium–molybdenum–vanadium low-alloyed steel 15Kh2MFA for the manufacture of reactor vessels, since it has a high radiation resistance and thermal stability [1, 2]. In foreign practice, chromium–molybdenum–vanadium steels, the analogs of steel 15Kh2MFA, have been used since the beginning of the 1990s for the manufacture of large-sized vessels of hydrocracking reactors [3–6]. Owing to a high content of alloying elements (Ceq ≈ 0.8% [7]), these steels are restrictedly weldable. Despite an almost identical chemical composition inherent in steels 15Kh2MFA-A mod. A and that of steels 2¼Cr–1Mo–¼V, the metal of their welded joints exhibits a significant difference in the content of basic alloying elements, such as chromium, molybdenum, vanadium, and nickel.

A higher operating temperature of hydrocracking oil reactor vessels (up to 454°C as compared to 350°C, the maximum temperature of VVER vessels) and the presence of a hydrogen-containing medium requires the prevention of creep and hydrogen embrittlement to provide the identity of the chemical composition of weld metal. The materials used for the manufacture of modern VVER reactor vessels demand stringent requirements on strength characteristics; therefore, the tempering temperature of welded joints in VVER vessels made of steel 15Kh2MFA-A mod. A is significantly lower (660–680°C as compared to 700–720°C for welded joints in the case of 2¼Cr–1Mo–¼V steels), which necessitates a decrease in the content of the main alloying elements in the weld metal in comparison with the base metal.

At CRISM Prometey, new welding materials have been developed for the automatic welding of VVER vessels made of steel 15Kh2MFA mod. A, and the vessels of oil hydrocracking reactors made of steel 2¼Cr–1Mo–¼V, which provides enhanced operating characteristics of welded joints [8, 9]. To develop scientifically based technological parameters for welding using novel materials, it is of interest to study the formation of metal microstructure in a welded joint upon cooling over a wide range of cooling rates under the conditions of multipass welding.

MATERIALS AND METHODS

To study the effect of the cooling rate exerted on the structural–phase transformations, we used samples of the weld metal made of the following materials:

—welding wire Sv-15KhGMTA in combination with an agglomerated flux 48AF-71 (for welding VVER vessels made of steel 15Kh2MFA-A mod. A);

—welding wire Sv-15Kh3GM1FTA in combination with an agglomerated flux 48AF-70 (for welding of the vessels of oil hydrocracking reactors made of steel 2¼Cr–1Mo–¼V).

The chemical composition of the weld metal, whose samples were prepared for testing, is presented in Table 1.
For performing the dilatometric studies, a BAHR Termoanalise DIL805 high-speed quench-deformation dilatometer was used.

The samples were cylinders 10 mm long and 5 mm in diameter made of a welded joint in a narrow cut. To provide the identity of the chemical composition and the structure of metal, they were cut from the central part of the weld in three rows (Fig. 1).

The heating time to a temperature of 1100°C was 10 min for each sample; the cooling rate in the temperature range from 200 to 727°C (the temperature range of austenite decay [10]) was varied from 0.5 to 500°C/s.

The metallographic studies were carried out on the end surfaces of the samples using an Axio Observer A1m light microscope. The hardness was measured on the cross sections of the end surfaces of the samples using the Vickers method in accordance with GOST (State Standard) 2999-75 using a Tsvik 5030SKV hardness tester at a load of 10 kgf (~1 N).

**RESULTS AND DISCUSSION**

The onset of phase changes upon the decay of supercooled austenite was determined from the inflections of lines characterizing the length of a sample depending on the decrease in temperature shown in Fig. 2. The change in the metal structure of the samples as a function of cooling rate is shown in Figs. 3 and 4. The results of hardness measurement are shown in Fig. 5. The diagrams of isothermal austenite transformation (C curves [11]) shown in Fig. 6 for the studied materials were plotted on the basis of the results of dilatometric and metallographic studies, as well as hardness measurements.

The boundary between the bainite and martensite regions is conditional on the basis of hardness measurements, since it is rather difficult to separate these structural components using optical metallography. A comparative estimate of the diagrams presented in Fig. 5 shows that the critical points \( A_c1 \) and \( A_c3 \) for sample A are positioned 30–35°C lower than those for sample B. This can be explained by the fact that sample A contains nickel in the amount of 0.63% (see Table 1), which, as is known [11], significantly enhances the stability of austenite. The martensite region in the case of sample B is substantially shifted to the right, which, to all appearances, can be explained by a higher content of chromium, molybdenum, and vanadium (see Table 1). The increased content of these elements leads to the inhibition of diffusion transformations upon cooling below point \( A_c1 \) [11]. The microstructure of sample A at cooling rates from 500 to 100°C/s is represented by martensite (Figs. 3a, 3b), a solid solution of \( \alpha \)-iron supersaturated with carbon. As is seen in Fig. 5, this range of cooling rates corresponds to the

**Table 1. Chemical composition of weld metal**

<table>
<thead>
<tr>
<th>Sample marking*</th>
<th>Welding wire/flux</th>
<th>Content of elements, wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>A</td>
<td>Sv-15KhGMTA/48AF–71</td>
<td>0.078</td>
</tr>
<tr>
<td>B</td>
<td>Sv-15Kh3GM1FTA/48AF–70</td>
<td>0.072</td>
</tr>
</tbody>
</table>

* Further, the samples of weld metal made of steel 15Kh2MFA-A (VVER reactors) and the samples of weld metal made of 2¼Cr–1Mo–¼V (hydrocracking oil reactors) are named A and B, respectively.