Study of the structural state of the metal welded joint 2.25Cr-1Mo-V steel depending on the parameters of post-weld heat treatment

Titova T I, Shulgan N A and Borovskoy A S

«TK «OMZ-Izhora» Ltd, 13/BM Finlyandskaya st., 196650, St. Petersburg

E-mail: tatyana.titova@omzglobal.com

Abstract. The results of studies of the structural state and properties of welded joints of steel 2.25Cr-1Mo-V after various modes of post-weld heat treatment are presented. The study of all zones of the welded joint using an optical microscope at magnifications up to 1000 times was conducted. It was established that the structure of the weld metal and HAZ of the welded joint 2.25Cr-1Mo-V steel in all thermal conditions is represented by bainite with different contents and distribution of the carbide phase. The level of hardness of the welded joint in Vickers units according to ASTM E92 is studied. The following critical values of the Larsen-Miller parameter were determined: for which the weld metal and HAZ ensure the absence of brittle structures with hardness higher than 350 HV10, exposed to hydrogen and the formation of cold cracks, at which the required level of hardness for trouble-free operation is not more than 248 HV10 and at which the coagulation of carbides is too intense and leads to a decrease strength properties.

1. Introduction

As is known, modern petrochemical reactors are highly loaded pressure vessels, the materials of which are subject to very strict requirements for the level of service properties – a high level of "cold" and "hot" strength, cold resistance, taking into account the operation at low climatic temperatures, and others [1-3]. For the production of such reactors, materials of the 2.25Cr-1Mo-V alloying system are used, which are prone to cracking during welding, so the technology of their welding and post-welding heat treatment is complex and requires knowledge of the processes of structure formation.

In the manufacture of the petrochemical reactor vessel from 2.25Cr-1Mo-V steel, all pressure welds are subjected to immediate post-weld heat treatment, which is divided into low-temperature dehydrogenation heat treatment (DHT) and intermediate stress relieved heat treatment (ISR, high tempering), and then a final post-weld heat treatment (PWHT, high tempering) is performed to form operational properties. As a rule, the welded joint of the 2.25Cr-1Mo-V alloying system passes the following manufacturing sequence: welding → DHT → technological operations → ISR-technological operations → PWHT. In this case, the first seam of the reactor vessel Assembly may be subjected to more than ten high tempering, and the closing seam of the reactor vessel to only one high tempering of PWHT.
2. Materials and methods of research
Experimental welds made of 2.25Cr-1Mo-V steel were made by automatic submerged welding method for the research. The welding materials used for this purpose had a type of alloying close to the base metal (table1). After welding, the welded joints were subjected to heat treatment according to the following modes: DHT (\(P_{LM} = 13.0\)), ISR (\(P_{LM} = 19.0-19.6\)), PWHT (\(P_{LM} = 20.3-21.6\)).

| The weld joint area          | The content of elements, wt. % |
|-----------------------------|--------------------------------|
|                             | C     | Cr    | Mo   | V     | Mn   | Si   | Nb   | P     | S     | As   | Sn   | Sb   |
| Base metal                  | 0.13  | 2.38  | 1.01 | 0.28  | 0.48 | 0.07 | 0.01 | 0.006 | 0.002 | 0.004 | 0.003 | 0.001 |
| SA-336V F22V                |       |       |      |       |      |      |      |       |       |       |      |      |
| Weld metal 2.25Cr-1Mo-V     | 0.10  | 2.49  | 1.08 | 0.35  | 0.86 | 0.17 | 0.02 | 0.007 | 0.003 | 0.003 | 0.007 | 0.0006 |

3. Findings and discussion of results
The study of the structural state of the metal of different zones of the welded joint by direct method using an optical microscope at magnifications up to 1000 times and indirect method, namely determination of the level of hardness of the welded joint by Vickers method according to ASTM E92. The effect of thermal treatments on the structure and properties of the weld metal was expressed through the release parameter-Larsen-Miller parameter (\(P_{LM}\)). The Larsen-Miller parameter (\(P_{LM}\)) is calculated by the formula [4]:

\[
P_{LM} = TK(20+10\tau) \times 10^{-3},
\]

where TK - the temperature of exposure in degrees Kelvin, \(\tau\) - the duration of the release, hour.

The criterion of acceptability of the metal structure of the welded joint 2.25Cr-1Mo-V steel was considered the absence of pronounced coagulation of carbides, which leads to a sharp decrease in the strength and stress-rupture of the steel.

As is known, the bainite structure characteristic of the weld metal of 2.25Cr-1Mo-V steel is optimal for ensuring operational properties, including a high level of low-temperature impact work, tensile strength and fluidity in the PWHT state [5]. However, the bainite structure formed during welding is characterized by a high hardness - more than 350 HV<sub>10</sub>, which indicates its high sensitivity to hydrogen, and therefore to the formation of cold cracks [5, 6]. Obviously, the parameters of the ISR in the process of manufacturing the product should provide a hardness of not more than 350 HV<sub>10</sub> in all areas of the welded joint.

In order to reduce the tendency of petrochemical reactor vessel metal to crack during operation under the influence of hydrogen sulfide-containing medium at high temperature and pressure, it is necessary to ensure the metal hardness of welded joints not more than 248 HV. This requirement is included in all standard specifications for the manufacture of modern petrochemical reactor housings.

In the present study, it was found that the structure of the weld metal and HAZ of the welded joint of 2.25Cr-1Mo-V steel in all thermal states is represented by bainite with different content, distribution of the carbide phase. HAZ has a fine-grained structure, the weld metal consists of sections of large-crystal and fine-grained structure. Figure 1 shows the change in the structure of the weld metal as the value of the \(P_{LM}\) increases. After heat treatment with the tempering parameter \(P_{LM} = 13.0\) (350°C), the structure of the weld metal and HAZ is close to the original (after welding), and therefore has similar properties. An increase in temperature-time parameters of tempering to \(P_{LM} = 19.3\) and above is accompanied by the release of carbides, an increase in their size and quantity, and coagulation...
along the grain boundaries (Figure 1 b, c), which should lead to a decrease in the tensile strength of the metal and its stress-rupture properties [7]. Tempering with \( P_{LM} \) much higher than 21.0 is impractical, as it leads to intensive coagulation of carbides, and with \( P_{LM} \) more than 21.6 to the dissolution of small and the formation of large carbides (Figure 1 d).

![Figure 1](image)

**Figure 1.** Microstructure of weld metal after various post welding thermal treatments: a) 13.0 \( P_{LM} \) (350°C), b) 19.3 \( P_{LM} \), c) 20.3 \( P_{LM} \), d) 21.6 \( P_{LM} \). Etching is performed with 4% alcohol solution HNO₃.

Changes in the level of hardness of welded joints of 2.25Cr-1Mo-V steel were evaluated in the state after welding and after tempering with \( P_{LM} = 13.0-20.6 \). The results of determining the hardness depending on the tempering parameter \( P_{LM} \) are shown in figure 2.

![Figure 2](image)

**Figure 2.** Hardness of various zones of welded joints 2.25Cr-1Mo-V steel in various thermal states

As a result of researches it is established that in a condition after welding (before heat treatment) the level of hardness of welded connection made in metal of a seam - to 398 HV, in metal of HAZ - to 397 HV. High values of hardness in the weld metal and HAZ immediately after welding indicate the presence in these areas of the weld brittle structures prone to cracking. At the same time, the initial hardness level of the thermally improved base metal is quite low, it does not exceed 250 HV₁₀ and
subsequently, when increasing the $P_{LM}$ to 20.2, it decreases to 220 HV$_{10}$. After DHT with $P_{LM} = 13.0$, performed at 350°C, immediately after welding, the level of hardness of the welded joint is close to the initial (post-welding) level and is in the weld metal-up to 374 HV$_{10}$, in the metal of HAZ - up to 387 HV$_{10}$, which corresponds to the presence of brittle structures prone to cracking in the presence of hydrogen. These data suggest a high probability of cracking is in the weld metal or HAZ, where the hardness exceeds the critical level of 350 HV$_{10}$. Thus, the DHT of welded joints of 2.25Cr-1Mo-V steel applied directly after welding, to remove hydrogen, does not significantly affect the reduction of hardness and can only be used when providing a low initial level of hydrogen in the weld metal and HAZ. To reduce the hydrogen content in the welded joint, a lower temperature mode DHT can be used [8].

According to the data presented in figure 2, to reduce the hardness below the critical value of 350 HV$_{10}$ and confirm the absence of brittle structures in the metal of welded joints of 2.25Cr-1Mo-V steel, the $P_{LM}$ tempering parameter must be at least 19.2 (Figure 2). An increase in the $P_{LM}$ tempering parameter to 19.6 leads to a more significant decrease in the hardness level: in the weld metal-to 279 HV$_{10}$, in the HAZ - to 264 HV$_{10}$.

However, tempering with the $P_{LM}$ parameter up to 19.6 does not allow achieving the required level of weld hardness for defect-free operation-no more than 248 HV$_{10}$. In accordance with the graphical representation of the dependence "$P_{LM}$ tempering parameter - hardness" to ensure the hardness of welded joints of 2.25Cr-1Mo-V steel below 248 HV$_{10}$, it is necessary to temper with the $P_{LM}$ parameter $> 20.15$. The implementation of the experimental mode of post-weld heat treatment with the tempering parameter $P_{LM} = 20.2$ at a temperature of 695°C led to a decrease in the hardness of the weld metal to 242 HV$_{10}$, which is close to the maximum permissible values. However, after tempering with the parameter $P_{LM} = 20.2$, the hardness drop over the cross-section of the welded joint reaches 50 HV$_{10}$, which indicates the possibility of structural stresses and uneven strength characteristics. Obviously, the PWHT temperature should be increased. The use of tempering with a holding temperature of 700°C ($P_{LM} = 20.3$) showed that it is not only more effective than tempering at 695°C ($P_{LM} = 20.3$), reduces the level of hardness of the welded joint (up to no more than 236 HV$_{10}$), but also provides a smaller hardness drop across the cross section of the welded joint -38 HV$_{10}$. Thus, a PWHT regime with a temperature of 700°C corresponding to a $P_{LM}$ of not less than 20.3 should be considered sufficient to ensure the required level of hardness of welded joints of 2.25Cr-1Mo-V steel of not more than 248 HV$_{10}$.

4. Conclusion
As a result of the performed studies of welded joints of 2.25Cr-1Mo-V steel, it was established that the absence of brittle structures with hardness above 350 HV$_{10}$ in the weld metal and HAZ, prone to hydrogen influence and formation of cold cracks, is provided at $P_{LM} \geq 19.20$. Guaranteed obtaining required for operation of a uniform level of hardness of not more than 248 HV$_{10}$ is possible during highpost-welding tempering, the temperature and duration of which exceed 20.3 $P_{LM}$. It was found that tempering with $P_{LM}$ being significantly higher than 21.0 is impractical, as it leads to intensive coagulation of carbides, and therefore to a decrease in strength properties. The established limits of the $P_{LM}$ tempering parameter values can serve as a basis for the development of temperature-time parameters of post-weld heat treatment of welded joints of 2.25Cr-1Mo-V steel for guaranteed absence of cold cracks in them in order to improve the safety and reliability of materials of pressure vessels such as petrochemical reactor housings operated in regions with low climatic temperatures.

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