Effect of heat treatment on the structure and properties of the chromium-nickel alloy G-35

V A Ermishkin, D L Mikhailov, S P Kulagin, N A Minina, N A Palyi

A.A. Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences, Leninskii pr. 49, 119334, Moscow, Russia

E-mail: Minina1951@rambler.ru

Abstract. This paper is devoted to the study of the nickel-chromium alloy G-35, which was intended for the manufacture of a chemical reactor vessel operating in molten chlorides in the temperature range of 550 - 650°C. A preliminary study of the structure and mechanical properties of the G-35 alloy was carried out in order to select the methods for their investigation. With the help of Photometric analysis of structural images it was found that the weld metal is in the austenitic state and the presence of an alloying of boron was also established. A class of functions has been established that describes the loading curves for three-point bending of samples.

1. Introduction

The choice of structural state of structural materials is associated with the search for answers to a number of important questions. Here we will not consider a complex of issues related to financial aspects of choice. The choice has already been made. It is dictated by the manufacturing conditions of the body of a chemical reactor operating in molten chlorides in the temperature range of 550 - 650°C. Among the mandatory requirements that must be met by the structural state of the nickel-chromium alloy G-35, should be mentioned: corrosion resistance in the working body of the reactor and, including, resistance to corrosion under voltage, heat resistance in a given temperature range, the necessary margin plasticity to perform rolling operations in the absence of heating, a sufficient level of technological strength in all operations for the manufacture of the reactor vessel, including weldability and heat treatment of product. Taking into account the fact that most of the material properties that must meet the above requirements are structurally sensitive, special attention should be paid to the kinetics of the structural evolution of the alloy and phase transformations occurring in the alloy during the entire technological period of its manufacture and its production cycle. The properties of the alloy should be studied taking into account the dynamics of structural transformations, both in the manufacture of the reactor and in its operation.

2. Materials and Methods

Passport data alloy G-35 (USA) are shown in Table 1. Preliminary estimates of the phase composition of nickel-chromium alloys can be obtained from the Schaeffler diagram, so you need to find chromium and nickel equivalents (in mass. %), \([\text{Cr}]_{\text{equiv}}\) and \([\text{Ni}]_{\text{equiv}}\) respectively, according to the formulae [1]:

---

[1]: Reference to the formulae and further discussion.

---
\[ [\text{Cr}]_{\text{equiv}} = (\text{Cr}) + 2(\text{Si}) + 1.5(\text{Mo}) + 5(\text{V}) + 1.75(\text{Nb}) + 1.5(\text{Ti}) + 5.5(\text{Al}) \text{ mass. %} \]  
\[ [\text{Ni}]_{\text{equiv}} = (\text{Ni}) + (\text{Co}) + 0.5(\text{Cu}) + 0.5(\text{Mn}) + 25(\text{N}) + 30(\text{C}) \text{ mass. %} \]  

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
& Mn & Al & C & Cr & Cu & Co & Fe \\
\hline
& 0.22-0.21 & 0.22-0.18 & 0.010-0.008 & 32.90-32.95 & 0.02-0.03 & <0.05 & 0.14-1.22 \\
\hline
W & 0.03 & 7.98-8.06 & 57.31 & 0.003 & <0.002 & 0.14-0.16 & <0.01 \\
\hline
\end{tabular}
\caption{The chemical composition of the G-35 alloy in mass. %}
\end{table}

The calculations showed the following results: \([\text{Cr}]_{\text{equiv}} = 46.62 \text{ mass\%}, [\text{Ni}]_{\text{equiv}} = 57.62 \text{ mass \%} \). Thus, the G-35 alloy, according to the Schaeffler diagram, should be a single-phase solid solution of all elements, martensite stabilizers in austenite, in an equilibrium state, but due to non-equilibrium crystallization conditions, fluctuations of concentration clusters occur, which can have considerable sizes. Photometric analysis of structural images (PHASI) allows us to provide qualitative and quantitative information on the distribution of secondary phase precipitates on the observation surface and in size, as well as on their chemical composition. Figure 1 shows an example of such an analysis of a sample of alloy G-35 in the initial state and in the cast state in the weld.

PHASI, developed at IMET RAS [2], is a software-analytical complex based on computer analysis using a differential scheme comparing the reflection brightness spectra and structures of surface fragments of the reference and test samples with the output of the analysis results in a visual graphic form, in the form of tables and graphs. Its physical fundamentals and methodological possibilities were previously discussed in a number of publications [3, 4]. Here we will focus only on the features of the application of PHASI as applied to the study of diffusion processes. It begins with scanning the surfaces of samples from chemical elements that are alloying components of the alloy under study on the one hand and a fragment of the surface of the object under study on the other. Digitized images of scanned images are entered into a computer, in which, first of all, according to a special program included in PHASI, the luminance spectra of the reflection of visible light from the surfaces of compared objects are compared. These spectra are constructed in the coordinates "spectral density of the brightness of the reflection - P(I) - intensity of the brightness of the reflection - I". The spectral density was determined by the formula:

\[ P(I) = \frac{n(I)}{N} \]  

where: \( n(I) \) is the number of pixels with intensity of brightness - I, \( N \) is the total number of pixels into which the analyzed image is divided. The abscissa axis shows the values of the intensity of brightness in the divisions of the linear scale, varying from zero, corresponding to the total absorption of incident visible light, to one - to its full reflection from the surface under study. Above the spectra, mathematical operations are used, which make it possible to reveal the characteristic features of the structure of the materials under study. Using color staining of intervals corresponding to the spectra of the standards, it is possible to isolate these features.
Figure 1. Comparison results of the base metal of the G-35 alloy. From above, the structure of the selected fragments, below them the spectra of the brightness of reflection of visible light from them: a) - with the weld metal (left panel) and initial state (right panel)

and then transfer this color to the images, i.e., identify those elements of the structure that contribute to the selected intervals of the spectrum. Using the alloying elements of the alloy under investigation as standards, one can study their concentrations on the observation surface, which are converted into volume concentrations by stereology methods. It can be seen from the figure that the base metal is homogeneous; its structural components are distributed evenly over the fragment, whereas the components painted in yellow and blue light have dropped out of the weld metal. Due to the fact that the material in the operating conditions will work for bending, the evaluation of its mechanical characteristics was also carried out during bending tests. Samples in the form of small beams with dimensions of $20 \times 4 \times 4 \text{ mm}^3$ were loaded according to the three-point bending scheme on an Instron-3382 testing machine with a speed of 1 mm/min. Before and after deformation, the lateral surfaces of the samples were photographed by a digital camera with subsequent analysis by the PHASI method.

3. Results and discussion
The alloy samples were studied in three structural states: the base metal after cold rolling (samples 8), the main deformed (8-d), cast weld metal (4-1) and weld metal after annealing $800^\circ\text{C}$ for 1 hour (4-2). To estimate the distribution of alloying elements, the PHASI method compared images of the structures of alloy fragments in the three listed states and the brightness spectra of the reflection of visible light from their surfaces with the standards of the alloying elements of the alloy under study. The peaks on the spectra of the standards were covered with intervals of 10 pixels wide, painted in the colors assigned to them: the peak on the chromium spectrum is colored magenta, nickel in blue,
molybdenum in yellow and boron in red. Figure 2 shows the results of the analysis, the surface of the sample in the initial state has the layered structure with grains elongated along the rolling direction forming lines. The structure is predominantly colored blue, but due to the overlap of some spectra, it is difficult to give an accurate estimate of the concentration of alloying elements on the surface of the fragments. The color of the surface fragments of welds, both after heat treatment and without it, is clearly dominated by the color of nickel. This can be seen by looking at the reflectance brightness spectra from nickel and chromium standards. It should be noted that the width of the spectra is greatly influenced by the quality of the preparation of their surface. The better it is, the narrower the spectrum. For rough surfaces are characterized by diffuse reflection and a wide range. Using the PHASI method, it was found that the G-35 alloy contains boron in an amount of 0.002 mass. %. Boron powder was used as a reference. Figure 3 shows the reflection spectra for nickel and chromium.

![Figure 2](image)

**Figure 2.** The structures of the studied states of the G-35 alloy at 125 times magnification: in the initial state (a); after welding (b); after welding and annealing (c).

Figure 4 shows the boron distribution on the studied alloy fragments. All elements of the structure, except for the painted ones, were absorbed. The range of the boron spectrum was colored blue. It can be seen from the figure that in both cases boron is located along the grain boundaries and in the form of precipitates at the nodal points of the grain grid. In the heat-treated weld, the discharge is larger.
Inside the grains there is a fine discharge of the red colored phase. This color was colored characteristic peak, which does not belong to any of the peaks in the spectra of the

![Image](a) ![Image](b)

**Figure 4.** Distribution of boron in the plane of observation of the surface fragments of the G-35 alloy: in the weld after heat treatment (a); in the base metal (b). × 970

main alloying elements of the alloy. The results of the analysis of mechanical tests showed that the deformation curves in the coordinates “load in kg P is a deflection arrow in mm f”. well described by logarithmic functions of the form:

\[ P(f) = a \ln(f) + b \]  

(3)

The parameters of the function (2) for samples of all three states, together with the values of the confidence level \( R^2 \), are given in Table 2.

| Alloy condition                  | a      | b      | R²   |
|----------------------------------|--------|--------|------|
| Initial (base) state (8)         | 53,22  | 251,4  | 0,986|
| Welded seam (4-1)                | 61,34  | 341,2  | 0,957|
| Welded seam + heat treatment (4-2)| 71,66  | 361,8  | 0,985|

Figure 5 shows a typical loading curve for samples of alloy G-35 (weld metal). A summary of the mechanical test results is given in Table 3.

![Image](chart)

**Figure 5.** Typical loading curve of G-35 alloy sample with three-point bending (weld sample 4-2)
### Table 3. The results of mechanical tests of the alloy G-35

| № | Sizes of samples, mm | Mechanical properties | P, mm | ρ, mm |
|---|----------------------|-----------------------|-------|-------|
| b, mm | h, mm | W, mm³ | σ₀₂, MPa | σ₃, MPa | δ, % | ϕ, % |
| 8-1д | 3.56 | 3.78 | 8,477784 | 253,38 | 520,65 | 26,7 | 25,92 | 6,00 | 0.00112 |
| 8-2д | 3.53 | 3.79 | 8,450879 | 244,36 | 477,75 | 24,5 | 27,17 | 7,20 | 0.00113 |
| 8-3д | 3.47 | 3.72 | 8,003208 | 240,21 | 434,85 | 24,4 | 28,02 | 7,10 | 0.00115 |
| 8-4д | 3.57 | 3.72 | 8,233848 | 285,42 | 391,95 | 20,1 | 23,76 | 3,43 | 0.00112 |
| 8-1 | 3.12 | 3.74 | 7,273552 | 292,03 | 657,15 | 33,7 | 27,87 | 4,63 | 0.00128 |
| 4-1 | 3.08 | 3.80 | 7,412533 | 279,28 | 649,35 | 33,3 | 28,90 | 4,62 | 0.00130 |
| 4-2 | 3.50 | 3.77 | 8,290858 | 320,77 | 639,60 | 32,8 | 29,78 | 5,33 | 0.00114 |

### Conclusion
1. A preliminary study of the structure and mechanical properties of the G-35 alloy was carried out in order to select the methods for their investigation.
2. By the PHASI method, it was established that the weld metal is in the austenitic state.
3. Alloying of the alloy with boron, not specified in the alloy passport, has been established.
4. A class of functions has been established that describes the loading curves for three-point bending of samples.

### Acknowledgments
The work was carried out according to the state task No. 007-00129-18-00 and with the financial support of the Russian Foundation for Basic Research (grant No. 17-08-00098a).

### References
[1] Saito Y, Onay B and Maruyama T 2012, *High Temperature Corrosion of Advanced Materials and Protective Coatings* (Elsevier).
[2] Ermishkin V.A., Murat D.P., Podbelsky V.V. Information technology of photometric analysis of fatigue damage of materials. *Information Technologies* 2007. 11, p. 65-70.
[3] Ermishkin V.A., Murat D.P., Podbelsky V.V. The system of photometric analysis of structural images and its application to the study of materials in fatigue conditions. *Instruments and systems. Management, monitoring, diagnostics.* 2008. 10 p. 38-44
[4] Ermishkin V.A., Minina N.A., Fedotova N.L. "Method of photometric diagnosis of phase transformations in solids according to the analysis of the brightness spectra of the reflection of light from their surface", Patent No. 2387978, 2010. Bull. №12.