Study of structural non-homogeneity impact on mechanical properties of dissimilar weld joints of carbon steel 20 and corrosion-resistant austenitic 12Kh18N10T steel

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Abstract. The paper is devoted to identifying features of structural non-homogeneities formation in dissimilar welded joints of carbon steel 20 to corrosion-resistant austenitic 12Kh18N10T steel, obtained by tungsten inert gas welding (TIG), as well as studying of their influence on the mechanical characteristics of welded joints under static and cyclic loading. Differences in the formation of a diffusion carbide interlayer in weld metal alloyed with nickel and manganese are established. When austenite is alloyed with nickel, bulk carbon diffusion occurs, while in manganese austenite boundary diffusion becomes the main mechanism for carbon diffusion, which occurs mainly along grain and sub-grain boundaries of austenite. As a result of mechanical tests, it was established that under static tension welded joint works under conditions of strengthening by a soft (ferritic) layer due to the restraint of transverse deformations by more solid (carbide) layer. The limits of soft interlayer dimensions, under which the softening of welded joint does not occur, are established that will allow to proceed to the extreme temperature-time parameters of heat treatment and operation of welded joint.

1. Introduction

Nowadays welded structures from dissimilar steels are used in many industry branches. The expediency of their use is caused by the operating conditions and the ability to reduce metal consumption, improve efficiency and durability. One of the most common options for combining materials in a welded joint is a combination of carbon or low-alloy steel, usually pearlite class, and austenitic corrosion-resistant chromium-nickel steel. For example, the task of welding specified classes materials arises when joining pipelines and steam pipelines with elements of power equipment at nuclear power plants. At the same time, taking into account inevitable non-homogeneity of chemical composition in the welding zone of dissimilar steels, under the influence of such operational factors as temperature and operation time prerequisites are created for carbon diffusion movement and formation of structural non-homogeneity in the weld. The general regularities of such processes have now been investigated [1-4]. The main reason for carbon diffusion is the difference in its thermodynamic activity in solid solutions of the materials being joined, which is due to the different alloying of these solid solutions. Thus, in the presence of alloying elements in the weld metal, forming stable carbides (Cr, Ti, Nb, W), cementite dissociates in the less alloyed steel and released carbon diffuses through the fusion boundary into the more alloyed weld metal with the formation of resistant carbides of alloying elements in it [1, 3]. Currently, work is underway to study the process of carbon
diffusion and properties of dissimilar welded joints for steels of various structural classes [5-15]. As the main way to suppress the carbon diffusion movement in welded joints, it is proposed to perform barrier deposition method with a high nickel content on less alloyed steel [6, 11, 15]. Welded joints are considered either in the state after welding or after a short-term post weld heat treatment.

The aim of this paper was to study the process of structural inhomogeneities formation in welded joints of carbon steel 20 and corrosion-resistant austenitic 12Kh18N10T steel under prolonged temperature exposure and to establish the influence of soft ferritic interlayer width on the results of tension tests and cyclic tests for the samples with a weld joint.

2. Research methods

Dissimilar welded joints of plates with a thickness of 10 mm from steel 20 and corrosion-resistant austenitic 12Kh18N10T steel, obtained by TIG, were investigated in this paper. Two types of filler wire were used – an “Autrod 308LSi” filler wire with low carbon content (0.01%) and nickel as the main austenizer and “G102” wire with a carbon content of 0.4% and manganese as the austenizer (without nickel). Welding was carried out in several passes in the gap in order to obtain a weld of constant width (Figure 1a). The chemical composition of filler wires, along with chemical composition of the materials to be welded, is given in Table 1.

![Figure 1. Gap filling scheme (a), welded plate cutting scheme (b) and sample for mechanical test scheme (c).](image)

**Table 1.** The chemical composition of welded steels and filler materials

| Material     | C   | Si  | Mn  | Ni  | Cr  | Cu  | Ti  | S   | P   |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 20           | 0.17-0.24 | 0.17-0.37 | 0.35-0.65 | <0.25 | <0.25 | <0.25 | –  | <0.04 | <0.04 |
| 12Kh18N10T   | <0.12 | <0.8 | <2.0 | 10.0 | 18.0 | <0.3 | 0.4-1.0 | <0.02 | <0.035 |
| 308LSi       | <0.03 | 0.65-1.0 | 1.4-2.1 | 9.0-11.0 | 19.5-21.0 | <0.3 | –  | <0.02 | <0.03 |
| G102         | 0.4  | 0.75 | 14  | –   | 14.5 | –   | –   | –   | –   |

All the welded plates were subjected to heat treatment at 650°C with different aging times for the formation of structural interlayers of different width. After each exposure, a series of flat samples was
cut off from the plate for metallographic studies and mechanical tests, after which the remaining part of the plate was heated again and held until the next aging time (Figure 1b). Before each heating, a protective carbon-free compound was applied to the surface of the plates in order to prevent intensive decarburization of samples surface due to its oxidation by the gas phase. Thus, the total maximum aging time was 300 hours. After cutting off a series of samples, a metallographic section was made, as well as 5 flat samples for mechanical testing (Figure 1c). The total number of test specimens was 55. It should be noted that spheroidization of cementite occurred in carbon steel during prolonged exposure at high temperatures, resulting in decrease in the ultimate stress of steel 20 base metal, as well as it was difficult to determine the boundary of ferritic interlayer. To restore the properties of carbon steel and the structure of its pearlite component, after the main heat treatment, a reducing heat treatment was carried out (heating up to 760 °C, holding for 15 minutes and air cooling). This made it possible to restore the pearlite component due to phase recrystallization and to increase the ultimate stress of carbon steel base metal. At the same time, the short-term exposure practically did not affect the picture of diffusion processes in the welded joint.

The microstructure of welded joints was studied using light microscopy methods. The length of the ferritic interlayer was measured by the bright field method on a Zeiss Axio Observer Z1m optical microscope. To identify the structure of carbon steel ferritic interlayer, a 4% solution of nitric acid in ethanol was used. In addition, this reagent made it possible to identify the overall structure of carbide interlayer without noticeably etching the grain boundaries of austenitic weld metal and base metal of 12Kh18N10T steel. Ultimate stress of welded joints was determined under uniaxial tension with the strain rate \( V_s = 2 \text{ mm/min} \). Cyclic tests were carried out by loading the samples with a pulsating tensile-unloading cycle (cycle asymmetry factor \( R = 0 \)) up to the maximum cycle tension \( \sigma_{\text{max}} = 360 \text{ MPa} \) with a frequency of \( f = 50 \text{ Hz} \) and determining the number of cycles before destruction.

3. Results and discussion
In the process of samples aging after welding at temperature 650 °C in the weld zone of carbon steel with austenitic steel structural changes were observed due to the carbon diffusion movement from the more alloyed weld metal to carbon steel. At the same time, from the side of steel 20, near the fusion line there is a ferritic zone, and with distance from the fusion line, particles of structurally free cementite appear. The presence of structurally free cementite is due to the change of carbon solubility in ferrite during heating and cooling. At the holding temperature (650 °C) the solubility in ferrite is higher than at a temperature of 20 °C, at which observation was carried out. Therefore, carbon, which at the aging temperature is in solution, at the observation temperature is released from this solution in the form of tertiary cementite. The subsequent restorative heat treatment at 760°C promotes the formation of a pearlite in this zone, which is detected in the microstructure as small colonies in large ferrite grains.

Further from fusion line there is a zone with partially disintegrated pearlite, followed by the base metal structure, in which no diffusion changes take place. The typical structure and hardness distribution for the decarburized zone in steel 20 is shown in Figure 2. The structure of completely decarburized zone (ferritic layer) has a number of distinctive features. Firstly, ferrite grains in this zone reach very large sizes. Their height reaches 180-600 μm, and in horizontal direction ferrite grain has a size that is equal to or close to the width of ferritic interlayer. That is, in fact, the ferritic interlayer consists of ferrite columnar grains, herewith the initial size of these structural components (before aging treatment) is within 5-15 μm for ferrite and 3-8 μm for pearlite. The second feature of ferritic zone structure is that very close to the fusion line there is a thin zone of fine ferrite grains with dimensions of about 5-15 μm. The width of this zone is about 25 μm. Ferrite grain width and size in this zone do not depend on the exposure time. A similar structure of decarburized zone is observed in all studied samples, both when using filler material with Ni, and with Mn.
Near the fusion line in the weld metal there is a zone of increased etching, in which carbides of elements with a greater affinity for carbon than iron are formed. For the steels considered, such a basic element is chromium. Titanium, which is part of austenitic steel, is available in it in the amount necessary for binding carbon, which is also available in this steel. Therefore, carbon coming from steel 20 through the fusion line boundary cannot be bound into titanium carbides. This is confirmed by the absence of titanium carbides and carbonitrides well detectable by light microscopy in the structure of weld metal. The presence of a certain amount of these inclusions is explained by their incomplete dissolution during welding or by repeated release at the stage of crystallization and cooling of weld metal. The main high-carbon phase released in the weld metal and detected during metallographic study is M_23C_6 or M_7C_3 type carbides [16, 17]. Taking into account that carbon diffusion rate through the fusion line is substantially lower than carbide formation reaction rate, it can be assumed that the only «consumer» of carbon coming from steel 20 is carbide phase. Therefore, the zone of increased etching, which contains carbides, repeats the zone of carbon diffusion penetration into the weld metal. Figure 3 shows the carburized zones for two types of austenitic weld metal. It was found that in case of alloying weld by Mn (G102), the carbon penetration distance from the fusion line turned out to be significantly longer, and the nature of the carbide phase indicates that carbon moved mainly along the grain boundaries (figure 3, a). With an aging time of 300 hours, carbon penetrated almost the entire width of the weld. In the weld alloyed by Ni, carbide phase release in the carburized zone occurs equally both at the boundaries and inside the grains (Figure 3b).

Given the fact that decarburized ferritic zone has a lower hardness and strength, it is this zone in the welded joint that will determine its strength characteristics. It was found that in the samples, the welds of which were obtained using a filler metal containing Mn, the decarburized zone length is greater at the same aging time. The growth rate of the ferritic interlayer was also higher in these welds.
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From the results of static tests (Figure 4) it follows that at small values of diffusion interlayers width, the welded joint strength is determined by the ultimate stress of steel 20, which is equal to 434...476 MPa. With increasing interlayers width the welded joint strength is determined by the strength of ferritic interlayer's metal, and the values of ultimate stress decrease with increasing of interlayer width.

![Figure 4](image)

**Figure 4.** Results of mechanical tests of weld joints: impact of soft interlayer width ($x/\delta$) on the ultimate stress $R_u$ (a) and on the number of cycles to failure $N$ (b).

Such nature of the change in the welded joints strength can be explained by the effect of soft interlayer contact hardening [18, 19]. In case of a sufficiently wide ferritic interlayer in the welded joint it goes through the plastic strain at stresses above 270 MPa, and in the central part of interlayer in the absence of durable adjacent sections, a transition to metal’s concentrated plastic deformation occurs with its subsequent destruction. On the contrary, in case of very narrow ferritic interlayer the effect of contact hardening appears. At stresses of about 400 MPa the concentrated plastic deformation of the ferritic interlayer, which causes the appearance of transverse deformations of the sample, is hampered by the presence of adjacent metal sections with more durable ferrite-pearlite structure. The adjacent to a ferrite-pearlite structure sections, involved in concentrated deformation, like the metal of ferritic interlayer, is characterized by a much more intensive stress-strain state with large values of acting true stresses and strains. It also has a greater metal strain hardening and at the same time has a very significant plasticity reserve. A further increase in load during tensile tests leads to concentrated deformation in the base metal of steel 20, which, due to a smaller plasticity reserve, is destroyed earlier than metal in the area of the ferritic interlayer, which withstands greater plastic deformation without destruction.

It should be noted that the absolute values of the ferritic interlayer width are not given, since the character of the weld joint deformation is determined not by the absolute, but by the relative width of the soft interlayer. The relative width is the ratio of the interlayer width $x$ to the smallest linear dimension $\delta$ of the sample cross-section (for the researched samples $\delta \approx 2$ mm). Thus, during short-term tests, it was established that welded joint metal softening occurs when the values of soft interlayer relative width are equal to 0.55 for both types of filler materials examined (Figure 4). However, given the higher growth rate of soft interlayer in a welded joint using filler material with Mn, metal’s softening of such welded joint occurs at shorter aging time than welded joint metal using filler material with Ni.

Cyclic tests of welds under investigation showed that in samples welded with both types of filler material, resistance to cyclic loading also depends on the interlayer width. Thus, in welded joints with narrow interlayers, zone with such interlayers does not weaken the welded joint, and the destruction of
all samples occurs along the base metal. With an increase in the interlayer width, the samples destroy along the interlayer with a monotonic decrease in the cycle number up to destruction (Figure 4).

4. Conclusions
The decarburized soft layer forms at the fusion line from the carbon steel side and consists of 3 structural zones (in the order of distance from the fusion line): large columnar ferrite grains (zone 1); large columnar ferrite grains and tertiary cementite inclusions (zone 2); ferrite-pearlite structure with partially dissociated cementite (zone 3). The greatest decrease in hardness occurs in zones 1 and 2, the decrease in hardness of zone 3 does not exceed 15% of the carbon steel base metal hardness. The growth rate of the ferritic interlayer is higher for welds alloyed with manganese instead of nickel, and the dependence of variation interlayer width on time differs from the parabolic one.

The diffusion movement of carbon in the weld metal alloyed with manganese occurs mainly along the grain boundaries. Under long exposures, carbon penetration is possible over the entire width of the weld. At the same time, the hardness of carburized zone in the welds with Mn is lower than in the welds with Ni due to the lower density of carbide inclusions.

The static short-term strength and cyclic strength of the welded joints under study is determined by the soft (ferritic) layer width. At small (less than 0.55) values of the soft interlayer relative width due to contact hardening, the strength of welded joints is determined by the strength of the least durable welded material, which is steel 20. With an increase in the relative width of the soft interlayer, its effect on the welded joint properties increases and destruction of welded joints occurs at lower stress (static tests), or with a smaller number of cycles (cyclic tests). The values of destructive stress under static short-term loading and the number of cycles up to destruction under cyclic loading monotonously decrease with increasing of interlayer width.

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