The effect of cooling speed on the structure and properties of the heat affected zone in welded compounds of ferrite-austenitic steels

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Abstract. Such parameters as the maximum heating temperature, duration of stay at high temperatures, the rate of cooling influence greatly the structure and properties of the heat-affected zone of welded joints of steels and alloys. In the present work, the effect of different cooling speed upon the impact of the thermal cycle of welding on the structure, the fine structure and toughness of ferrite-austenitic steels is investigated. It is established that the cooling speed after welding has a great influence on the shock impact toughness, the phase composition and the structure of the zone of ferrite-austenitic steels.

1. Introduction
The parameters of the thermal cycle of welding have great influence on the structure and properties of the heat-affected zone of welded joints of steels and alloys: the maximum temperature, the duration of stay at high temperatures, the speed of cooling. The scope of application of ferrite-austenitic steels is narrower than that of chromium-Nickel austenitic steels due to their embrittlement at welding temperatures and exploitation temperatures. Under the influence of the heat-affected zone, the intensive growth of ferritic grains is observed in the area of overheating as well as changing of the ratio of the phases and disintegration of unstable structures [1-3].

2. Materials and methods
The influence of cooling rates on the structure, the fine structure, and toughness of ferrite-austenitic steels Fe-0.08%C-22%Cr-6%Ni-1%Ti and Fe-0.08%C-18%Cr-8%Mn-2%Ni-1%Ti of industrial melting according to GOST 5632–72 under the heat-affected zone impact was investigated.

The study was carried out on the samples cut from the parent metal in the delivery condition, with subsequent simulation of the thermal cycle of welding on the installation of high-speed electric heating. Simulation of the thermal cycle of welding was conducted on the samples sized as 12 x 12 x 60 mm.

The sample was rigidly fixed by current-carrying copper water-cooled grips of the installation and was heated by passing current through the sample. The maximum heating temperature was 1300 °C, the heating rate was 100 °C/s, the cooling speed was 2, 10, 40, 100 °C/s. During the heating process, the heat affected zone of a welded joint was imitated, performed by automatic welding with submerged arc and electroslag welding.

The temperature at the center of the sample was controlled with the aid of chromelalumel
thermocouple caked in the sample. The entry mode was carried out using a potentiometer ‘KSP-4’ included in the control circuit. The speed of cooling was controlled via additional heating and in the air. The samples with shock type 11 [4] were produced out of the specimens with the heat affected zone. The incision was performed at the place of fastening of the thermocouple in the center of the sample.

Diffractometer DRF-2 was used for structural quantitative analysis of the metal. Hardness was determined according to Vickers (TPP-2) (GOST 2999-75) and microhardness of structural components was found out on the device ‘PMT-3’ according to (GOST 9450-76). The microstructure of the samples was studied on the microscope ‘MIM-8’. Fractographic study was carried out using electron microscopy in the fractures percussion samples in a transmission microscope ‘UEMB - 100K’.

The structure was revealed by electrolytic etching in oxalic acid. To separate the phases, staining reagent of Groesbeck was used. The ratio of α- and γ- phases was determined by metallographic and x-ray diffraction analysis according to standard techniques [5]. Fractographic investigation of the surface of impact specimens tested at a temperature of minus 40°C, was carried out at the maximum and minimum cooling rates of 100 and 2°C/s.

3. The study of the structure of steels Fe-0.08%C-22%Cr-6%Ni-1%Ti and Fe-0.08%C-18%Cr-8%Mn-2%Ni-1%Ti

The microstructure of the samples of steel Fe-0.08%C-22%Cr-6%Ni-1% Ti under the delivery condition and after simulation of the thermal cycle of welding is shown in Figure 1.

![Figure 1](image1.png)

**Figure 1.** The microstructure of steel Fe-0.08%C-22%Cr-6%Ni-1%Ti under the delivery condition (a) and the heat affected zone, the cooling rate of 40 °C/s (b), ×100.

Microfractogrammes of steel specimens Fe-0.08%C-22%Cr-6%Ni-1%Ti after exposure to the thermal cycle of welding with different cooling rates are shown in Figure 2.

![Figure 2](image2.png)

**Figure 2.** The fractures of steel Fe-0.08%C-22%Cr-6%Ni-1%Ti after exposure to the thermal cycle of welding at cooling of 2 °C/s (a), and cooling to 100 °C/s (b), x4500.
The results of the tests for impact toughness are presented in table 1. The fractogrammes of the samples cooled at a rate of 2°C/s are characterized mainly by ductile fracture. There are major foil allocations of carbides, clusters of carbides of dendritic form, a large selection of carbonitrides in the fracture.

**Table 1. Impact toughness of steels Fe-0.08%C-22%Cr-6%Ni-1%Ti and Fe-0.08%C-18%Cr-8%Mn-2%Ni-1%Ti after the influence of the heat-affected zone (T\text{max} = 1300 °C)**

| Type of Steel | Cooling Speed under heat affected zone, °C/s | Shock impact toughness, KCV, MJ/m² at temperatures, °C |
|---------------|---------------------------------------------|--------------------------------------------------------|
|               | base metal                                  | -40   | -20  | 20   |
| Fe-0.08%C-22%Cr-6%Ni-1%Ti | 2                                            | 0.84  | 1.15 | 1.35 |
|                | 10                                          | 0.15  | 0.18 | 1.10 |
|                | 40                                          | 0.18  | 0.50 | 1.20 |
|                | 100                                         | 0.30  | 0.61 | 1.30 |
|                | base metal                                  | 0.32  | 0.84 | 1.40 |
| Fe-0.08%C-18%Cr-8%Mn-2%Ni-1%Ti | 2                                            | 0.89  | 0.94 | 1.10 |
|                | 10                                          | 0.16  | 0.21 | 1.00 |
|                | 40                                          | 0.19  | 0.40 | 1.00 |
|                | 100                                         | 0.24  | 0.65 | 1.30 |
|                | base metal                                  | 0.32  | 0.87 | 1.55 |

The cooling speed has a significant influence on the impact strength of the investigated steels. With the increase in cooling speed, shock impact toughness also increases. The minimum values of the impact strength were obtained at the cooling speed of 2 °C/s, characteristic of the electroslag welding method at all the temperatures tested. At this cooling speed, the toughness of both steels in the temperature test of minus 40 °C, minus 20 °C is less than 0.20 MJ/m². The increase in the cooling speed of up to 10 °C/s increases shock impact toughness up to ~0.50 MJ/m² for steel Fe-0.08%C-22%Cr-6%Ni-1%Ti and up to 0.40 MJ/m² — for steel Fe-0.08%C-18%Cr-8%Mn-2%Ni-1%Ti at the test temperature of minus 20 °C. The values of shock impact toughness remain low – less than 0.20 MJ/m² for both steels at the test temperature of minus 40 °C. When exposed to the heat-affected zone with the cooling speed of 40°C/s, shock impact toughness rises a bit at all the temperatures tested.

The highest shock impact toughness for steels Fe-0.08%C-22%Cr-6%Ni-1%Ti and Fe-0.08%C-18%Cr-8%Mn-2%Ni-1%Ti was obtained at cooling speed 100°C/s. The duration of stay of the metal in the high temperature region increases with the decreasing cooling speed, i.e. the time for the occurrence of diffusion processes increases. Chromium from ferrite diffuses, forming chromium carbides. In the areas depleted of chromium, there is a transformation of δ - ferrite into austenite. The percentage content of austenite reaches a maximum of 25 % in steel Fe-0.08%C-22%Cr-6%Ni-1%Ti and 47 % — in the Fe-0.08%C-18%Cr-8%Mn-2%Ni-1%Ti steel at a cooling speed of 2 °C/s, which is due to the long duration of stay at high temperatures. With the increase of the cooling speed, the amount of austenite in the studied steels decreases, reaching a minimum value of 20 % in steel Fe-0.08%C-22%Cr-6%Ni-1%Ti and 35 % — in Fe-0.08%C-18%Cr-8%Mn-2%Ni-1%Ti at a cooling speed of 100 °C/s. At the cooling speeds of 2, 10, 40 °C/s, a part of the austenite is transformed into martensite, the formation of which is confirmed by the increase in the microhardness of the γ′ - phase (table 2), as well as the increase of the lattice parameter of the α - phase and the microstresses of the second kind (table 3).
The amount of martensite increases with the increase of the cooling speed. The metallographic examination of the microstructure showed that at high cooling speeds of ~100°C/s, in steel Fe-0.08%C-22%Cr-6%Ni-1%Ti, secondary austenite in the form of needles is formed mainly at the boundaries of ferritic grains. In steel Fe-0.08%C-18%Cr-8%Mn-2%Ni-1%Ti, the formation of secondary austenite inside the grains is observed [6-7].

With the decrease of the cooling rate, as it has been already noted, the number of austenite phases increases, and at a cooling speed of 2 °C/s, separate grains of ferrite are completely transformed into secondary austenite inside the grains [6-7]. The true width of the line (311) of the α'-phase of steels Fe-0.08%C-22%Cr-6%Ni-1%Ti and Fe-0.08%C-18%Cr-8%Mn-2%Ni-1%Ti decreases as the cooling speed decreases (table 3).
At a cooling speed of 40 and 100 °C/s, the lattice parameter of the \( \alpha \) - phase of steels Fe-0.08%C-22%Cr-6%Ni-1% Ti and Fe-0.08%C-18%Cr-8%Mn-2%Ni-1% Ti will increase to 0.2889 nm and 0.2876 nm, respectively. The lattice parameter of the \( \gamma' \) - phase with the increasing cooling speed increases in both steels as the process of carbide formation is impeded and the content of alloying elements, primarily chromium, in the solid solution increases.

The fractographic investigation of the surface of the tested samples at a temperature of minus 40 °C was carried out at the maximum and minimum cooling speed of 100 °C/s and 2 °C/s. The fractography samples cooled at a speed of 2 °C/s are characterized by mainly ductile fracture. There is large foil emission of carbides and clusters of carbides of dendritic form in the fracture.

4. Conclusion
At a cooling speed of 100 °C/s, in the fractures, the total number of precipitated carbides and carbonitrides is much smaller, and they are more fine. There are no coarse precipitates of dendritic type observed. Along with the ductile fracture, there are areas of brittle fracture.

Taking everything into account, the cooling speed after welding has a great influence on the shock impact toughness of the phase composition and the structure of the zone of ferrite-austenitic steels.

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