

# The Morphology of Intermediate Structures Formed During Bainite Transformation in HSLA Steels

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**Abstract:** The paper deals with the structure of bainite formed under the influence of thermal deformation cycles of welding in low-carbon bainitic class steels. Morphology features associated with the formation of mesoferrite and granular bainite determines the high cold resistance of welded joints.

## Introduction

A complex of mechanical properties of steel depends on the state of austenite before the accelerated cooling, speed of cooling, temperature of the  $\gamma \rightarrow \alpha$  transformation. These mechanical properties are associated with the formation of a particular morphology of bainite, largely depending on the level of alloying of steel [1].

Currently there is no unambiguous interpretation of intermediate structures that are observed in low-carbon low-alloy steels. According to the classification of the intermediate structures shown in [2], it is proposed to distinguish needle bainite, rack and pinion, and a globular (granular) bainite by the form of crystals.

The development of bainitic transformation in low-carbon low-alloy steels at high temperatures for a certain time, when redistribution of not only carbon but also other alloying elements in the chemical composition of steels is possible, allows to predict that even under the isothermal  $\gamma \rightarrow \alpha$  transformation a variety of morphological forms of bainite may exist [1, 3].

The study of the composition of intermediate structures in low-carbon low-alloy steels carried out in [4, 5] showed that at the isothermal decay bainite structures of different morphology are formed. In the upper temperature range, comprising 580-450 °C, decomposition of the austenite occurs by diffusion mechanism with the formation of mesoferrite (the term was proposed in [3]) and globular shape carbide  $(\text{Fe, Cr})_{23}\text{C}_6$ . At temperatures below 450 °C, the austenite decomposes at a shear mechanism at bainitic  $\alpha$ -phase with the selection of the carbide  $(\text{Fe, Cr, Mn})_3\text{C}$ .

The aim of this work was to determine the characteristics of bainite morphology, formed in the heat-affected zone (HAZ) of high-strength low-alloy (HSLA) steels.

## Material and methods of research

Material for research served as the industrial bottoms of steel 20Cr2Ni and 24Cr2Ni. The samples were exposed to both thermal and deformation cycles of welding (transverse welding stresses and elastic-plastic deformations) using the experimental setup according to the method described in [6]. The heating rate in the temperature range of phase transformations was 150 °C/s. The range of investigated



cooling rates of  $\omega_{6/5}$  from 0.35 to 17.0 °C/s spanned the full range of structures from ferrite-pearlite to martensite. The temperature of the sample was raised from 850 to 1350 °C in increments of 50 °C. The anisothermal decomposition diagram of austenite charts were supplemented by structural diagrams. Data on the development of stresses in the sample under test were obtained by means of a system of load cells resistance with data transfer to computer.

The phase composition, total and fine structure were studied by means of optical microscopy (NEOPHOT-32), x-ray analysis (DRON-2,0), transmission electron diffraction microscopy of thin foils (EM-125 and EM-125K). Chemical etching of the sections was performed on 4% solution of nitric acid in ethyl alcohol.

Grain size was determined by the method of secant with GOST 5639-82 using digital processing [7]. To identify the boundaries of former grain of austenite in the case of the collapse of the supercooled austenite in the shear-diffusion mechanism of the micro-sections were subjected to etching in a hot saturated solution of picric acid.

### The results of the study and their discussion

Structures, formed in the HAZ of HSLA steels were investigated based on the results of the research presented in works [8-10].

Top bainite, having a plumose structure, consists of a supersaturated carbon  $\alpha$ -phase and carbide particles located at the boundaries of ferritic plates (fig. 1, a). Lower bainite has a needle (martensite) structure. At its formation, due to the lower diffusion mobility of carbon, bainitic  $\alpha$ -phase to a greater extent is supersaturated with this element, and the carbides are distinguished mainly inside the plates of ferrite immediately after their formation (fig. 1, b).

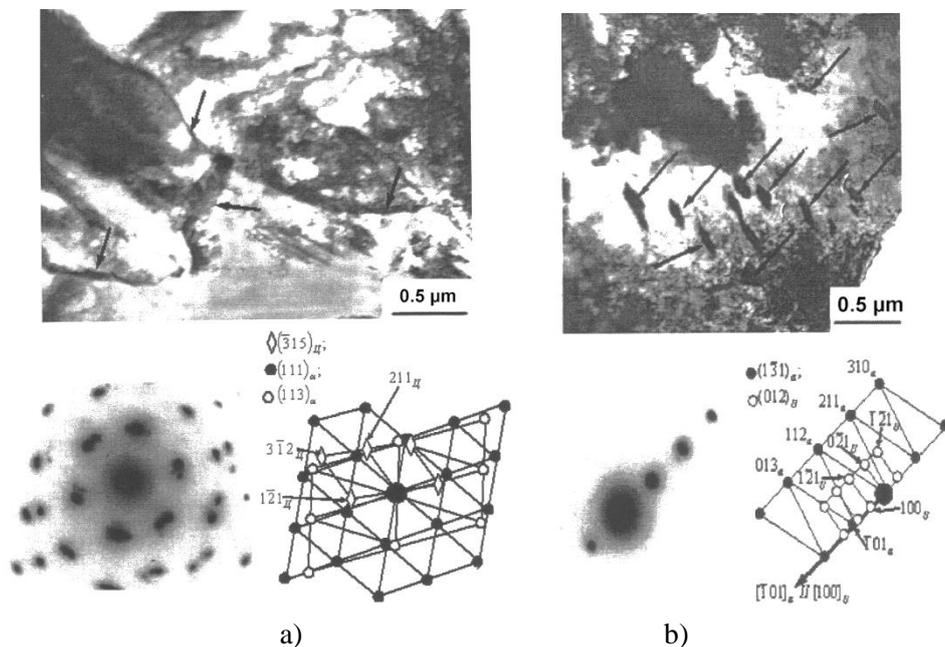


Fig. 1 – Bainitic structure, steel 24Cr2Ni (electronic microscopy with diffraction patterns): a) upper bainite; b) lower bainite, cementite particles are marked by arrows

Intermediate structures of granular morphology represent a multiphase mixture of mesoferrite, granular bainite, residual austenite, cementite and globular carbides. It is established that the chromium carbides, which do not have a specific orientation in the layout and differ from each other in particle size (fig. 2), together with  $\alpha$ -phase compose the basis of granular bainite [9].

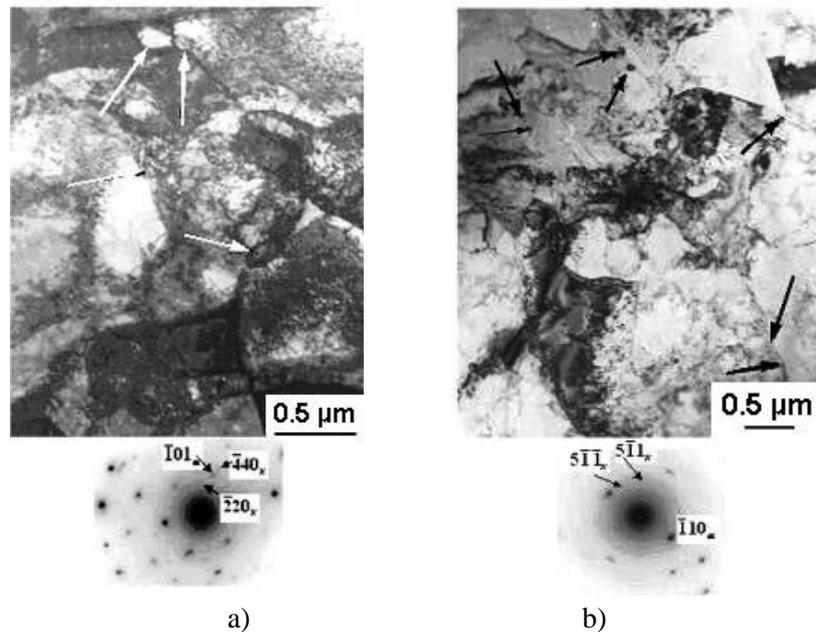


Fig. 2 – Bainitic structure, steel 20Cr2Ni (electronic microscopy with diffraction patterns): granular bainite, large (a) and small (b) globular chromium carbides  $(\text{Fe, Cr})_{23}\text{C}_6$  marked by arrows

Large particles having a diameter of approximately 200 nm are located mainly in the joints and on the borders of fragments of intermediate structures of granular morphology (fig. 2a). Their volume fraction in the individual local areas rises up to 10 %. Small carbides of globular shape with a diameter of about 10-20 nm are located mainly on the dislocations inside of all structural components of the  $\alpha$ -phase (fig. 2b). Despite the fact that the volume fraction of small carbides is not more than 0.2 %, their presence has a positive effect on the deformation capacity of the metal and it is the main factor preventing the birth of pockets of slow destruction [10].

In the first stage, the transformation is preceded by the fluctuation redistribution of carbon, resulting in individual local areas, which are depleted in carbon and become  $\gamma \rightarrow \alpha$  – transformation diffusion centers with the formation of mesoferrite with winding borders. Next comes the increase in the number of misoperates due to the removal of carbon from adjacent to the front of recrystallization sections of austenite with simultaneous appearance of new centers of crystallization of the  $\alpha$ -phase. High temperature bainitic transformation and a greater degree of hypothermia contribute to the diffusion mobility both carbon atoms and the atoms of carbide-forming elements.

Because the rate of redistribution of carbon is high, large amount of  $\alpha$ -phase both bainite and mesoferrite origin is quickly produced, which covers and blocks the unconverted austenite and gives it either a sort of islet inclusions on the background of fragmented ferrite and mesoferrite, or interleaving inclusions on the background of the rack and pinion and needle bainite. The emerging volume changes cause not only bainite  $\alpha$ -phase hardening, but the carbon-enriched austenite inclusions as well. As a result, there is a large number of crystal structure defects in the latter, serving as centers of crystallization of the carbides of globular shape in the allocation of carbon.

The formation of globular carbides contributes to the heterogeneity of the austenite, as in the carbon content and in the content of carbide-forming elements, which is inevitable in high speed at its collapse. In the enriched carbon austenite during bainitic transformation the formation of globular products of decay is possible, as  $\alpha$ -phase and carbides, which does not contradict modern ideas about the nature of bainitic transformations in steels [11-13].

Advanced hot plastic deformation in the austenitic region has a significant influence on phase transformation during continuous cooling and, consequently, to the formation of the final structure.

Plastic deformation in the austenitic region, above 50 %, leads to a partial growth of grain and increasing the stability of austenite, the upper bainite and structurally free ferrite are formed. The presence of the structural imperfections in austenite, crystal structure defects and concentration gradients caused by hot plastic deformation lesser extent causes the formation of intermediate structures of granular morphology, and shifts the region of their formation towards higher cooling rates and temperatures of transformation.

Microplastic deformation develops along the grain boundaries of austenite (the locations of the large carbides of the type  $Me_{23}C_6$ ) and inside them (the location of the fine carbides of the type  $Me_{23}C_6$ ), which greatly facilitates the process of accommodation of grains in the total plastic deformation, reduces the level of internal stresses at slow speeds relaxation, and contributes to the increased dispersion of the emerging structures. After hot plastic deformation and continuous cooling in a typical the HAZ interval velocity, volume fraction of lath bainite is minor, mostly there are mesoferrite and granular bainite. The increase in cooling rates leads to changes in morphology of a resulting bainite from granular to needle. The formation of needle structures in the whole volume of the original austenite grains leads to a significant heterogeneity. Ferrite is allocated along the former grain boundaries of austenite.

### Conclusions

1. In high-strength low-alloy steel carbon significantly affects the intensity and temperature range of decomposition of austenite to mesoferrite and granular bainite. In addition to carbon, bainitic structure in the heat-affected zone is determined by the grain size and homogeneity of austenite, dependent on heat input of welding.
2. The crystal structure of bainite in high-strength low-alloy steels subjected to thermal cycle of welding is characterized by high density of dislocations and subgrain structure. It is connected not only with the development of phase  $\gamma \rightarrow \alpha$  – transformation in the formation of intermediate structures of granular morphology, but also with the defects of the crystal structure acquired by the austenite at microplates deformation, inherited by bainitic structure. Peculiarities of morphology associated with the formation of mesoferrite and granular bainite determine the high cold resistance of welded joints.

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