# LASER AND HYBRID WELDED JOINTS OF LOW-ALLOY HIGH-STRENGTH STEELS: THE RELATIONSHIP OF STRUCTURE AND OPERATION PROPERTIES.

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Low-alloyed high-strength steels are widely used in various branches of modern industry, including construction, agricultural, transport, engineering and defense, for the manufacture of welded metal structures. Machinery and constructions of critical purpose require the use of steels of a wide class of strength in a fairly wide range of mechanical properties and, accordingly, of different structural and phase composition. Many structures of high-strength steels are structures of long-term use under external loading conditions. Therefore, the study of the influence of structural factors on the mechanical properties and crack resistance of welded joints of these steels becomes important. Nowadays in the manufacture of these metal structures, mechanized or automatic welding in shielding gases is used. Often they are replaced such progressive technologies as laser and hybrid laser-arc welding, which allow to obtain welded joints at increased speed with much smaller dimensions of welds and heat-affected zones (HAZ), as well as to improve the quality of joints of high-strength steel and the to raise productivity of their manufacture.

## Objectives of the research

Our main idea is to obtain welded joints with high operational properties, using both traditional and advanced welding technologies by selecting the requisite modes for each process. The aim of the work was to determine the regularities of influence of the structural-phase composition of the metal of welded joints of low-alloyed high-strength steel on the mechanical properties of these joints; revealing ways to optimize the welding process parameters (heating and cooling rates, heat input) for each method (laser and hybrid laser-arc) fusion welding.

## Techniques and equipment

A comprehensive approach is needed to solve this problem. We adhere to it and recommend everyone to do it. Its essence consists in carrying out materials science research at all structural levels from grain to dislocation. This is done using three types of microscopy: Optical microscopy, Analytical scanning electron microscopy, and Transmission electron microscopy. Optical microscopy allows determining: size and microhardness of grains and volume fraction of the phases of the structure. Analytical scanning electron microscopy allows determining: chemical composition size and distribution of phase particles and make fractographic analysis**.** Transmission electron microscopy allows determining: density and distribution of dislocation, substructures, segregations.

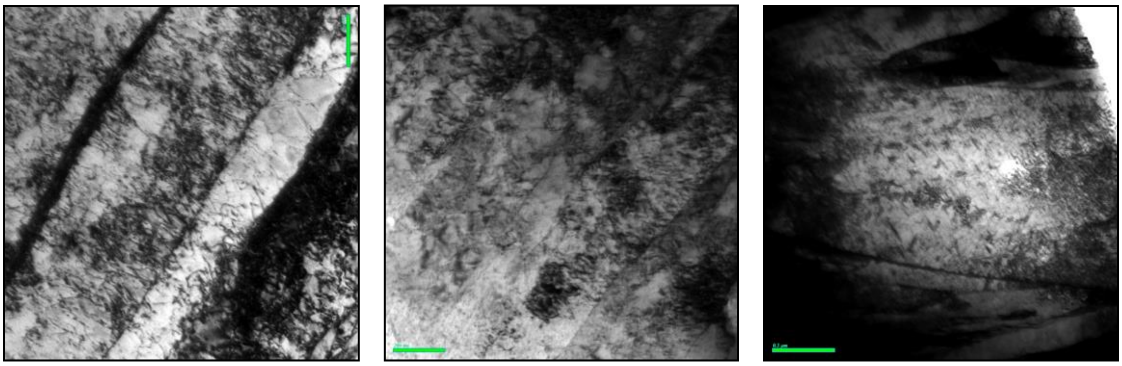
## Results and Discussion

Studies were carried out on samples of welded joints of high-strength steel (0.14% C) with an 8 mm thick bainite-ferrite structure produced by an laser (modes #1-#3) and a hybrid laser-arc (modes #4-#6) welding. In the case of  hybrid laser-arc welding, filler wire was used. Nd: YAG-laser DY 044 was used as a source of laser radiation. Table 1 presents the parameters of the welds: the weld width, the total width of the HAZ and the width of the overheating zone − I HAZ as the most important zone. The small dimensions of welds and HAZ should help reduce the level of local internal stresses in the metal of welded joints and increase their crack resistance.

Table 1. Welds and HAZ parameters and their mechanical and structural properties.

| No. | Weld | | | | HAZ | I HAZ | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Width (*mm*) | Micro-hardness (*MPa*) | Grain sizes ($\mu m$) | Dislocation density ($cm^{-2}$) | Width (*mm*) | Width (*mm*) | Micro-hardness (*MPa*) | Grain size ($\mu m$) | Dislocation density ($cm^{-2}$) |
| #1 | 5.0 | 2850…3510 | 50…90×150…410 | $(2…4)\cdot10^{10}$ | 2.0 | 0.4 | 3830…4170 | 50…90 | $(4…6)\cdot10^{10}$ |
| #2 | 4.0 | 3450…4010 | 30…100×120…400 | − | 1.9 | 0.3 | 4010…4420 | 30…80 | − |
| #3 | 3.3 | 3870…4330 | 20…40×100…400 | $(4…6)\cdot10^{10}$ | 0.8 | 0.25 | 4010…4250 | 30…60 | $(8…10)\cdot10^{10}$ |
| #4 | 4.0 | 3800…4010 | 30…120×170…350 | $(4…6)\cdot10^{10}$ | 1.9 | 0.3 | 3540…3900 | 30…60 | $(6…8)\cdot10^{10}$ |
| #5 | 4.3 | 4050…4420 | 30…80×150…300 | − | 1.6 | 0.35 | 3830…4010 | 25…50 | − |
| #6 | 4.2 | 3360…3940 | 20…80×150…250 | $(6…8)\cdot10^{10}$ | 1.4 | 0.23 | 3360…4010 | 20…40 | $(8…10)\cdot10^{10}$ |

In laser welding, studies have shown that at 880 J/mm (#1) a bainite-ferrite structure is formed in the weld metal and HAZ, mainly the $B_U$ (correspondingly 55% and 35%), Fig. 1a. When the heat input decreases to 316 J/mm (#3), the phase composition of the weld metal and HAZ changes from bainite-ferrite to bainite-martensite, Fig. 1b, c. Also crushing of the grain and subgrain structure in 1.3...1.4 times occurs with a certain increase in microhardness. Fine-grained grain structure of lower bainite ($B_L$) is mostly (45...50%) formed under conditions of uniform redistribution of the volume dislocation density in the weld metal $\rho = (6...8)\times10^{10}$ $cm^{-2}$, and in the metal of HAZ $\rho = (8...9)\times10^{10}$ $cm^{-2}$.



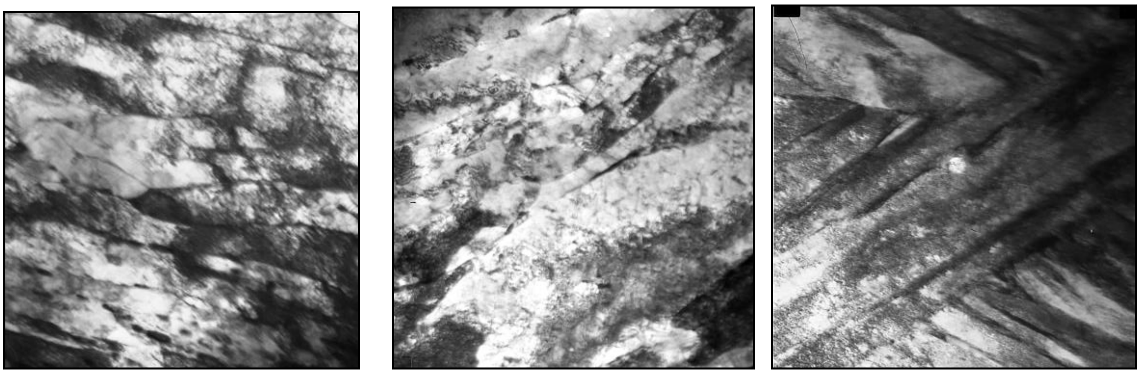
*a* *b* *c*

Fig. 1. The microstructure of welded joints produced by laser welding at 880 J/mm (a); 316 J/mm (b, c).

Studies of the structure and phase composition of welded joints in hybrid laser-arc welding have shown that when going from 363 J/mm (#4) to 314 J/mm (#6), the phase composition of metal of the weld and the overheated HAZ remains the same (bainite-martensite). However, the volume fraction of $B_L$ decreases noticeably (up to 10...20%). Herewith, in the case of 314 J/mm, the integral value of the dislocation density increases to $\rho = 1.5\times10^{11}$ cm$^{-2}$ and the mostly structure of the $B_U$ is formed, Fig. 2c. And the most uniform distribution of dislocation density $\rho = (4…6)\times10^{10}$ cm$^{-2}$ is characteristic for the $B_L$ structures at 363 J/mm, Fig. 2a, b.

It should be noted that in this case an increase in the density of dislocations is observed while a decrease in heat input from 363 J/mm to 314 J/mm. Perhaps this is due to a change in the ratio of the contribution of the arc and laser components of the hybrid process in the resulting value of heat input, namely, with a relative increase in the contribution of the arc component from 39% to 54%.

As a result of mechanical testing of welded joints, it was found that the most stable values of strength and ductility are characteristic of laser welding conditions. However, welded joints produced by hybrid laser-arc welding are characterized by the highest ultimate strength. Herewith, the optimal structure, from the point of view of phase composition (mainly $B_L$, more than 50%) and a gradient-free dislocation density distribution, is formed at 363 J/mm with a maximum contribution to the heat input of the laser component.



*a* *b* *c*

Fig. 2. The microstructure of welded joints produced by hybrid welding at 363 J/mm (a, b); 314 J/mm (c).

**Conclusions**

The structure and properties of welded joints of low-alloyed high-strength steel depend on the welding methods and the modes used.

Under various welding conditions, the following structure transformations are observed: the ratio of the phase components forming in the welding zones (lower bainite, upper bainite, martensite), as well as their parameters and volume fraction, changes.

Hybrid laser-arc and laser welding is characterized by the formation of lower bainite structures with significant refinement of the grain and subgrain structure with a uniform distribution of the dislocation density.

A significant increase in strength, ductility and crack resistance of welded joints of low-alloyed high-strength steel at a decrease in heat input and a transition to laser and hybrid laser-arc welding evidences the validity of the relationship "welding method (modes) → structure → properties".

**REFERENCES**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