Structure and mechanical properties of laser-arc hybrid welding of 13Mn6 steel welded with austenitic filler

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Abstract. In this article low-alloy structural steel 13Mn6 is welded by hybrid laser-arc welding. To increase the homogeneity of the weld metal during welding, an austenitic filler wire was used. To find out the working characteristics of the joint obtained by the HLAW method, metallographic studies were carried out, the microhardness of the welded joint was measured, tests for static tensile strength and static bending were carried out, and fatigue properties of the joint were also investigated. HLAW with the use of austenitic wire can positively influence the properties of the welded joint. In addition, when welding parameters vary, there is a possibility of penetration of the filler material to the entire depth of penetration, as well as to some partial value of its penetration. The article considers the principal possibility of joining heterogeneous materials on the example of 13Mn6 and 308SS steels.

1. Introduction
13Mn6 low-alloy structural steel is widely used in various industries. The working temperature range of 13Mn6 steel varies from -70 to 425°C, which allows its use for the manufacture of pipes, rolled metal products and structures used in such conditions. In the process of welding of this steel there are observed the heterogeneities associated with polymorphism. Along with welding of similar materials, there is a need for dissimilar joints. To achieve the aim of welding dissimilar materials it is necessary to study the phase diagrams of these materials [1]. The topic of research on welding heterogeneous materials is relevant, and brazing is also used for these aims [2-4]. There are a large number of types of welding for different applications, also to achieve homogeneity of the weld using different methods, such as ultrasound [5-11].

A lot of work was done on welding TRIP, DP and TWIN steels [12-14], mechanical properties and microstructure are studied.

In the present article the possibility of using austenitic filler in the process of HLAW during welding of steel 13Mn6 is investigated. This will allow not only to find out the applicability of the filler material different from the composition of the welded material, but also to evaluate the fundamental possibility of welding steel 13Mn6 with 308 Stainless steel. The analysis of microstructure, microhardness of the weld, static tensile strength, fatigue properties and static bending of the welded joint is carried out.
2. Materials and methods

Studies of Hybrid Laser Arc Welding (HLAW) welds were carried out on 13Mn6 low-carbon steel sheets. Chemical composition of steel is given in Table 1. Plates with thickness of 5 mm and size of 300×120 mm were used as blanks.

|                | C   | Si   | Mn  | Ni  | S    | P    | Cr  | Cu  | V    | Fe  |
|----------------|-----|------|-----|-----|------|------|-----|-----|------|-----|
| 308LSi         | 0.65-1.00 | 0.65-1.00 | 0.65-1.00 | 0.65-1.00 | 0.65-1.00 | 0.65-1.00 | 0.65-1.00 | 0.65-1.00 | 0.65-1.00 | 0.65-1.00 |
| 13Mn6          | 1.2-1.6    | 1.2-1.6    | 1.2-1.6    | 1.2-1.6    | 1.2-1.6    | 1.2-1.6    | 1.2-1.6    | 1.2-1.6    | 1.2-1.6    | 1.2-1.6    |

The scheme of obtaining samples is shown in figure 1. The IPG YLS-15 Ytterbium Fiber Laser was used to obtain the welded joints, the wavelength of which was 1.03 µm. During welding the laser radiation was directed perpendicularly to the plane of the workpieces, the focus of laser radiation was on the plane of the front surface of the welded workpieces. Plane-parallel workpieces were fixed on the welding table by a mechanical device. There was no air gap between the welding plates to be welded.

The arc welding torch was located behind the laser source at a distance of $D_{LA}=3.0$ mm. The welding torch was deflected by an angle of 50°. Austenitic welding wire 308LSi, 0.8 mm thick, the chemical composition is shown in Table 1, the wire feed speed is 6 m / min. Power of laser beam during welding was 8 kW, arc current - 187 A, arc voltage - 22.7 V, welding speed - 2 m/min.

![Figure 1. Laser-arc hybrid welding scheme.](image-url)

From the received welded joints on the electrospark discharge machine samples for carrying out of researches of structure of a seam and its mechanical properties were cut out. The investigations of macro- and microstructure were carried out with the use of the metallographic microscope Altami MET 1C. The etching of the samples was carried out in two stages, first in solution No.1 (4 ml HNO₃ + 96 ml C₂H₅OH) to reveal the structure of steel 13Mn6, then in electrolytically in solution No.2 (10 ml H₂C₂O₄ + 90 ml H₂O), at voltage of 4 V, during 30 seconds.

The mechanical properties were studied as follows. The first method was to measure microhardness using the Vickers method on the microhardness meter Duramin 5 at a load of 50 g. Due to the obvious non-penetration of the filler material into the heat-affected zone, microhardness measurements were made only from the front side of the weld of the arc source melting zone to the root of the weld, which is the melting zone of the laser source. The vertical measurement line shows the changes occurring with the transition from the arc source melting zone to the melting zone of the laser source.

The second method was to study static tensile strength. The studies were carried out on samples of standard size. Static tensile strength tests were carried out on a Testsystems 110M-10 testing machine at room temperature.
The third method was to investigate fatigue properties. The research was carried out on the BISS UT-04-0100 testing machine. Three amplitude stress values were taken for the research: 0.30-0.85, 0.30-0.80, 0.30-0.75% of $\sigma_B$. The tests were conducted at 80 Hz.

The fourth method, static bending, was carried out on a Testsystems 110M-10 testing machine. The tests continued until the time the crack was created.

3. Welded seam structure
To identify the microstructure of the HLAW welded joint using an filler material in the form of an austenitic wire, two etching stages were used. The first stage consisted in chemical etching in solution No.1. As a result, the structure of the heat-affected zone (HAZ) and the weld structure in the laser melting zone were identified. The reagent used is suitable for identifying the structure of 13Mn6 steel, but did not reveal the structure of the seam with an austenitic filler.

The second step was to etch electrolytically in solution 2. This type of etching made it possible to determine the structure of the upper zone seam where austenitic steel is present.

Figure 2a shows a macro picture of the HLAW welded joint with austenitic filler. As can be seen in the picture, the shape of the weld does not change in comparison with the usual HLAW. In the upper part of the seam, austenite is observed, its structure is characteristic of this type of welding, when the dendrites of austenite grow normally from the boundary of the molten metal to the centerline of the seam until they meet at the seam centerline. The microstructure of the fusing boundary of the austenitic filler and HAZ steel 13Mn6 is shown in figure 2b. There is a clear boundary and hardened structure of 13Mn6 steel in the HAZ zone. The transition zone between the arc melting zone with austenitic filler in the weld and the melting zone by laser source is shown in figure 2c. In this zone there is an abundant flow of austenitic filler into the melting zone by laser source, as can be seen by the etching quality of the weld metal and inhomogeneous structure is formed due to the flows arising in the welding process. The microstructure of the melting boundary of the laser source, as with conventional laser welding, represents an inhomogeneous structure of steel 13Mn6, subjected to polymorphic transformations.

4. Microhardness
The microhardness distribution in the weld metal shows its maximum value below the surface of the weld face for 1 mm and averages 5.45 GPa. Then there is a gradual decrease in the microhardness values, and at the boundary between the melting zones of the laser source and the arc value decreased to 4.70 GPa. In the melting zone of the laser source, the microhardness continues to decrease to 3.45 GPa. The decrease in microhardness in the melting zone of the laser source can be explained either by a large mixing of austenite at the top of the melting zone by the laser, or by the process of tempering due to the
boundary conditions of the welding workpiece. In this case, as described above, austenite mixing is present. Also, due to some widening of the root joint, it is possible to judge about excess energy input with further tempering, when the heat flow, reflected from the lower boundary of the workpiece, flows in the opposite direction. As a result, it is possible to judge about the double contribution of microhardness values distribution in the melting zone by the laser source.

5. Static tensile and fatigue properties
Steel 13Mn6 is subject to polymorphic transformations. During the welding process, HAZ is a heterogeneous structure with a significant increase in hardness, and thus strength. The static tensile test data on three samples showed the strength of the base metal to be 538 MPa, with failure occurring outside the welded seam.

The results of fatigue properties studies at the stress amplitude of 30-85\% of $\sigma_B$ showed the specimen failure in the region of the base metal, after $20.5 \times 10^3$ cycles. Further, after reducing the stress amplitude to 30-80\% of $\sigma_B$, the initiation and growth of the crack occurred at the boundary of fusion with an austenitic filler in the upper part of the seam. The fracture occurred after $13.24 \times 10^4$ cycles. After reducing the stress amplitude to 30-75\% of $\sigma_B$, the initiation and growth of the crack occurred along the entire boundary of arc and laser source fusion. The fracture occurred after $29.50 \times 10^4$ cycles. The dependence of the number of cycles on the stress amplitude is shown in figure 4.
6. Static bending
The front side and root of the HLAW welded joint were tested for static bending. Figure 5 shows the result of the static bending test on the front side of the weld. As can be seen, the stronger material, the remelted austenitic filler, is less subject to the static bending test than the adjacent HAZ. The most sensitive area for cracks was the fusion boundary between the austenitic arc filler and HAZ, with cracks forming on both sides of the fusion zone. The cracks originated at a bending angle of 101°.

Figure 5. Static bending test result for the weld front side.

The static bending test result for the weld root is shown in figure 6. Cracks are not formed at the root of the joint after a bend of 115°. But, as can be seen in figure 6c,d, cracks are formed on both sides of the melting zone by an arc source where an austenitic filler is present.

Figure 6. Static bending test result of weld root (a, b), formation of cracks after bending on the inside, in the area of austenitic filler (c, d).

7. Conclusion
Hybrid laser-arc welding of low-carbon steel using an austenitic filler is performed. On the basis of the studies performed the following conclusions can be drawn:

- The welded joint is non-defective and the weld shape does not differ from that of a conventional HLAW weld;
- When austenitic filler is added to the HLAW process, the weld structure is more homogeneous;
- There is a decrease in the microhardness of the weld metal in the direction from the weld face (5.45 GPa) to the weld root (3.45 GPa);
According to the results of static tensile tests, the failure occurs on the base metal;
At the strain amplitude of 30-80% and 30-75% of σB, in the study of fatigue properties of fracture occurs exactly on the boundary of fusion;
Crack formation at static bending occurs always along the boundary of fusion of austenitic filler and HAZ.
As a consequence, special exploitation requirements must be followed when welding dissimilar metals such as 13Mn6 and 308 Stainless Steel.

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