Weldpool shape investigation in fiber laser welding of Cr-Ni-Mn-N austenitic steel

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Abstract. Austenitic stainless steels are the main material for liquid natural gas tanks. Traditional Cr-Ni steels can be replaced by cheaper Cr-Ni-Mn-N ones, but there are difficulties with the implementation of welding for such materials, including nitrogen losses and hot cracking. Fiber laser welding can be applied to partially solve these problems, however the process optimization is needed to provide the optimal weldpool shape. In this work it was shown that the increasing of the laser beam power leads to the appearance of the second plasma torch and the area of open surface of the weldpool on the back side increases significantly, that can influence the interaction between the melted steel and the environment.

1. Introduction

Austenitic stainless steels are the main material for tanks for liquid gas transportation. They have optimal properties combination, but traditional Cr-Ni austenitic steels are expensive because of the high nickel concentration. This element is responsible for the γ-Fe structure stability, corrosion resistance in some aggressive environments and high low-temperature ductility. Nevertheless, nickel is a rare and expensive alloying element and the decreasing of its concentration in the steel makes it cheaper.

For the low-temperature application, the stable austenitic structure is required, thus the nickel concentration reduction must be compensated by the increasing of the part of Mn and N in the steel composition. Steels with the Cr-Ni-Mn-N alloying system have higher strength [1] and they are cheaper than Cr-Ni analogs, but they also have lower ductility [1] and corrosion resistance [2]. The optimal composition of the steel depends on the exploitation requirements. In the same time, the steel processing during the parts manufacturing can cause changes in the chemical composition. That is especially important if the steel has high nitrogen concentration for providing the austenite stability, such as in the new material [3] developed in MISIS for liquid natural gas tanks. This steel has both high mechanical properties and low nickel concentration, but the decreasing of the amount of nitrogen can cause the structure instability.

Welding is the main process that leads to the nitrogen concentration decreasing [4], however the laser welding application is able to reduce nitrogen loses [5] if the heat input is not redundant [6]. Using CO₂ lasers for large structures welding is difficult because of the special laser beam transportation system is needed. High-power fiber lasers are convenient tools, but there is a little data about the welding of nitrogen-containing steels with a beam of a fiber laser. It is known [7] that the surface layer of the melted steel and the plasma have higher temperatures than in case of the arc welding, in the same time the period of time when the metal is liquid and the weldpool open surface area are significantly lower.

The investigations carried out for the arc welding [8] shown that the weldpool open surface area, the volume of melted metal and the period of time the metal is in a liquid state are important parameters for the analyzing of the kinetics of nitrogen absorption and desorption. The problem of nitrogen loses can be partly solved by means of the addition of nitrogen to the shielding gas, but the concentration of nitrogen is limited by the porosity formation in the welded metal [9]. A complex approach including both the welding atmosphere composition...
choice and the welding parameters optimization for performing weldments with high properties is needed.

It is difficult to investigate the shape of a weldpool. For the fiber laser welding of the mild steel the influence of welding parameters on the weldpool shape was studied in [10], but there is no data about the influence of laser welding parameters on the main geometrical indicators of the melted metal pool for Cr-Ni-Mn-N steels.

In this work, the influence of the laser beam power and the welding speed for different focal positions of the beam on the area of the weldpool open surface and on the period of time the metal is in a liquid state are studied. The results can be used for calculations of the nitrogen exchange between the liquid steel and the environment.

2. Materials and the equipment
The samples for experiments were made of 12Kh17G9AN4 steel, its chemical composition is presented in Table 1. The samples were plates, their size was 100 × 50 × 3.9 mm, the butt welding of plates was carried out along their long sides. The IPG-Photonics fiber laser YLS-15 was used, the metal mirror optical system with the 600 mm focal length was applied for the beam focusing. The special device shown in Figure 1 was used for the melted metal removal during the laser welding process [11].

| Element | Fe | C   | Si  | Ni  | P   | S   | Cr  | N    |
|---------|----|-----|-----|-----|-----|-----|-----|------|
| Wight conc., % | balance | ≤ 0,12 | ≤ 0,8 | 3,5 – 4,5 | ≤ 0,035 | ≤ 0,02 | 16 – 18 | 0,15 – 0,25 |

![Figure 1. The device for removing the melted metal from the weldpool [11]](image)

3. Results of the weldpools investigation
The laser beam power and the welding speed were ranged for two focal positions: the first position was on the sample surface, the second was 10 mm lower, thus the beam was defocused and the power density increased with the depth. The beam diameters on the sample front surface were respectively 0,45 mm and 1,2 mm. Front and back weldpool open surfaces areas and the period of time the metal was liquid were measured for all welding parameters configurations. The results of measurements are presented in Figure 2 and Figure 3.
Figure 2. The weldpool geometrical parameters and the period of time the metal is in a liquid state duration for welding with the focused beam
Figure 3. The weldpool geometrical parameters and the period of time the metal is in a liquid state duration for welding with the defocused beam
On the front side, the area of a weldpool mainly depends on the beam diameter and it does not change significantly with the laser beam power changing or the welding speed changing. In the same time, on the back side, the area of a weldpool depends on welding parameters. It increases with the laser beam power increasing and decreases with the increasing of the welding speed. The weldpool length on the back side exceeds the weldpool length on the front side if the laser beam power is higher than some certain value and it determines the duration of the period of time the metal is in a liquid state. That explains the graphs in Figure 2c and Figure 3c.

The scheme of the evolution of the longitudinal cross-section of the weldpool with the laser beam power increasing is presented in Figure 4. The scheme is more suitable for that case when the beam is defocused, but in general it also describes a weldpool changing when the beam is focused.

**Figure 4.** The evolution of the longitudinal cross-section of a weldpool with the increasing of the laser beam power
The fiber laser radiation is not so effectively absorbed in a keyhole as the CO$_2$ laser radiation, that is why the part of its power that reaches the bottom of the weldpool is higher. The redundant energy causes the second plasma torch formation on the back side of the weld, and thus increasing of the laser beam power leads to the increasing of the melted metal surface area on the back side of the weldpool. This phenomenon is to be taken into consideration when the melted metal interaction with the environment and with plasma torches is studied.

The longitudinal section shape presented on the last picture in Figure 4 has a negative effect on hot cracking resistance According to the hypothesis expressed by V. S. Gavriliuk, hot cracks can be "healed" by the melted metal above the crystallization front. An example of a crack is shown in Figure 5. Nevertheless, it is impossible in case when the weldpool has the shape as it is shown on the last picture in Figure 4. The first type of the weldpool shape (Figure 4) is optimal for high hot cracking resistance.

![Image of hot crack on crystallization front](image)

**Figure 5.** A hot crack on the crystallization front

4. Conclusions
On the basis of investigations carried out, the following conclusions can be made:

- the application of fiber lasers is a perspective method to solve problems in C-Ni-Mn-N steels welding;
- the weldpool open surface area on the back side of the weld significantly increases with the laser beam power increasing and the second plasma torch appears under the weld;
- accurate optimization of welding parameters is needed to realize a complex approach to the nitrogen loses limitation, that includes the shielding gas composition choice and the weldpool shape optimization.
- laser welding parameters must provide the optimal shape of the weldpool for high hot cracking resistance and at the same time for low nitrogen loses.
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