# LASER WELDING OF LOW ALLOYED STEELS: INFLUENCE OF EDGE PREPARATION

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The objective of the research is to investigate an increase in efficiency of the high power laser welding process by the effect of two factors: joint edge surface roughness, and air gap between the plates. Welding of St3 low alloyed steel 20 mm thick was performed with high power fiber laser with a wavelength of 1070 nm at a power of 14 kW. Optimum roughness levels and recommended air gap between the plates to ensure maximum penetration depth and highest quality of weld are presented. 26 Ref., 5 Figures

***Keywords:*** *laser welding, low alloyed steel, fiber laser, high power, absorptance, penetration depth, gap, roughness of edge surface*

Methods to increase the absorption and, therefore, efficiency of the welding process, are an important component of modern deep penetration laser welding, as the absorption affects the process parameters: power level needed for the welding process, production speed, and weld quality. The absorption level also determines whether deep penetration or keyhole welding is achieved. The keyhole is a metal vapor cavity that is formed when the power density at the laser–metal spot of contact achieves a sufficiently high level (~$10^6$ W/cm$^2$). Material melts along the front wall of the keyhole as the laser beam moves, and the molten material is then transported via the side wall to the back wall, where it solidifies and forms a narrow weld. The laser beam is reflected multiple times on the walls of the keyhole (Figure 1).

The absorption level is not a fixed determinant but is a function of the material properties, surface treatment and environment parameters. All these factors have a critical impact during formation of the initial keyhole [1–3].

Possible way of increasing the efficiency of the process is using preheating techniques. Use of the preheating requires typically more work phases than laser beam welding and it increases the complexity of the welding process considerably. Use of hybrid techniques, despite the significant advantages (like higher process stability, less porosity and cracking, greater flexibility) has a perceptible disadvantage: high complexity of the equipment setup, and more parameters that should be controlled and optimized comparing to laser beam welding [4–7]. Main purpose of the study is to find a relatively easy way to increase the efficiency of the laser beam welding in the workshop conditions. Therefore, the influence of the edge surface roughness and the effect of the pre-set air gap were investigated.

The relationship between absorption and edge preparation has been widely investigated in $CO_2$ laser welding. Arata and Miyamoto presented

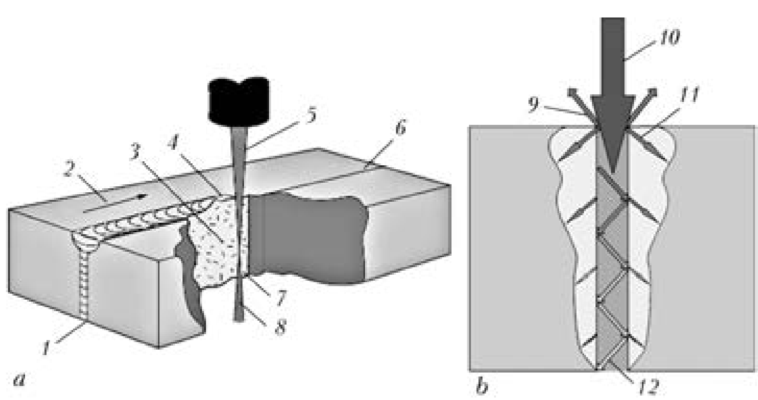


**Figure 1.** Keyhole welding process [4]: *1* — weld bead; *2* — welding direction; *3* — HAZ; *4* — keyhole; *5*, *10* — laser beam; *6* — weld edge; *7* — molten metal; *8* — laser beam exiting the workpiece; *9* — reflected radiation; *11* — absorbed radiation; *12* — multiple reflections on the keyhole walls

comprehensive results for the $CO_2$ laser absorption characteristics of metals in 1972 [8]. It was recorded that the absorption has a tendency to increase with the surface roughness, however, when the surface melts, the absorption decreases to a constant value. Some studies of laser beam welding have suggested that the influence of the edge surface roughness on the absorption is insignificant [6, 7]. However, results from other sources have indicated an increase in the absorption in roughened surfaces compared to fine polished ones [1, 9–12].

Laser welding research with Nd:YAG and high power fiber lasers to date has tended to focus on optimizing beam and mechanical parameters, and relatively little attention has been paid to surface preparation of the joint edges [13–20]. Bergstrom et al. [21] reported on the correlation between the absorption level and surface roughness with Nd:YAG laser surface treatment. It was found that the absorptance of the surface increases with roughness once a certain threshold has been exceeded. This phenomenon was explained by multiple scattering events.

It has been suggested that the absorption increase with increase in edge surface roughness may be explained by increase in the air gap size between the plates during butt joint laser welding [22, 23].

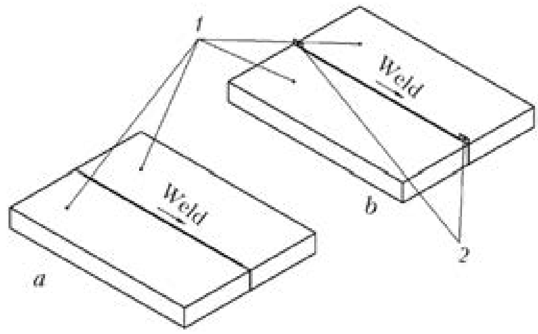


**Figure 2.** Welding setup for butt joint laser welding (*a*) and butt joint laser welding with pre-set air gap (*b*): *1* — steel plate; *2* — steel strip

The aim of this article is to contribute to the research data of thick section laser welding by investigating the influence of edge preparation on the weld quality and performance.

**Experimental.** Welding experiments with the high power fiber laser IPG YLR 15000 were performed on the St3 structural steel plates in the Laser Welding Laboratory of Saint-Petersburg State Polytechnic University, Russia. Randomly chosen pairs of samples were selected for chemical analysis. The alloying composition of the St3 steel according to GOST 380–94 [24] was as fol-

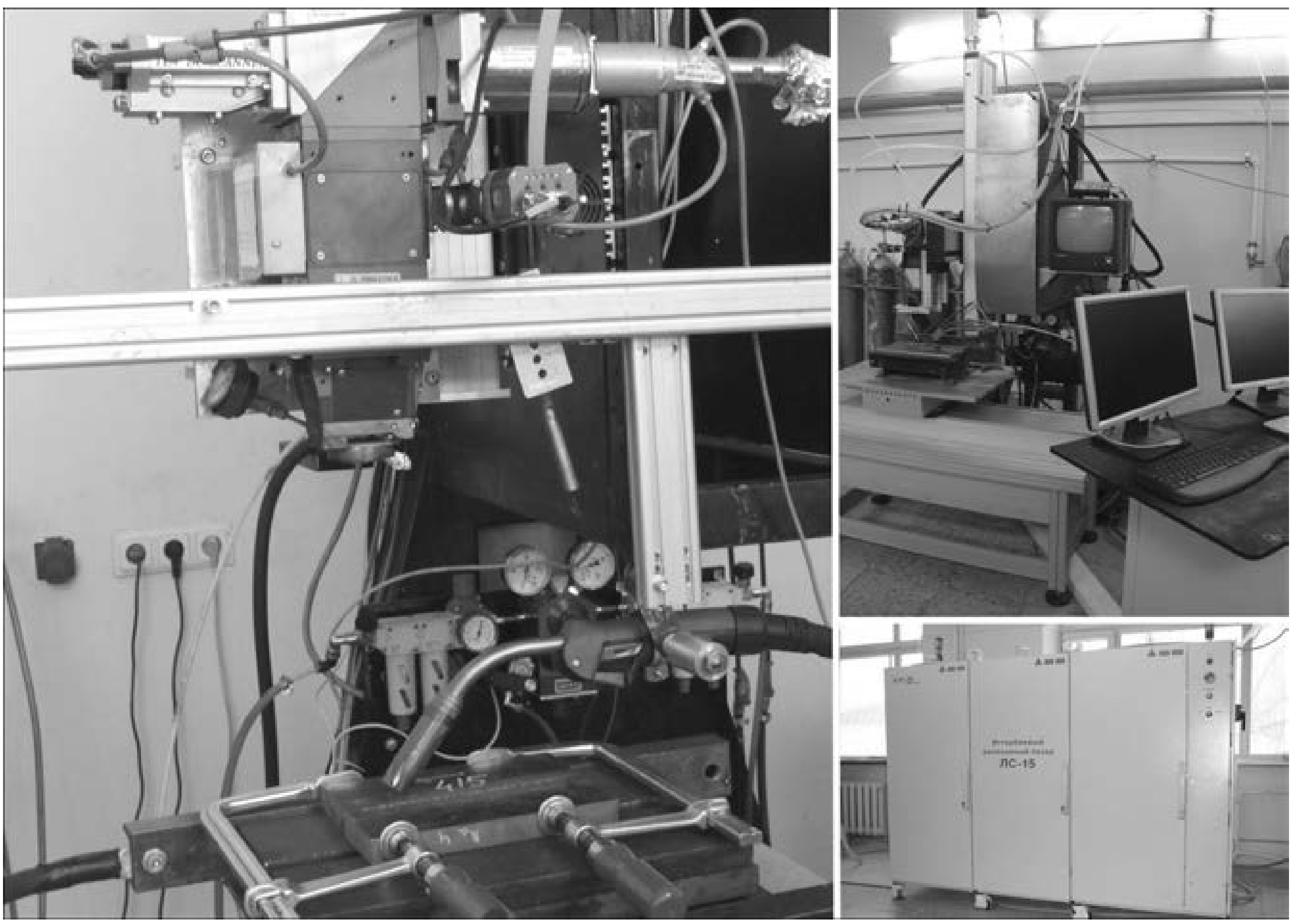

**Figure 3.** Thick section laser welding setup at focal length of 400 mm and focal point diameter of 0.4 mm

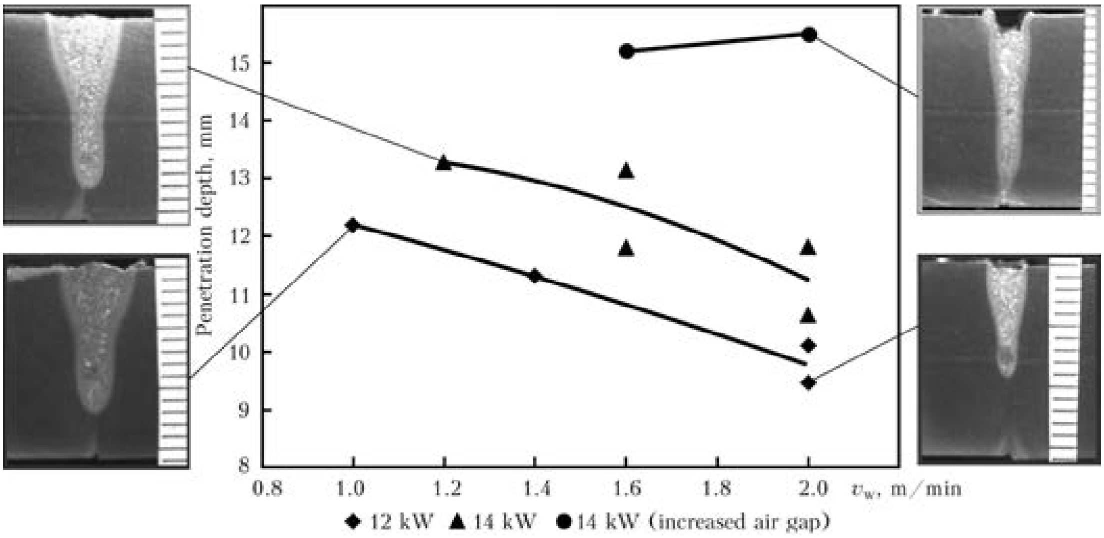


**Figure 4.** Depth of penetration of St3 steel 16 mm thick at different parameters of laser welding

lows, wt.%: 0.16C, 0.19Si, 0.44Mn, 0.01P, 0.01S, 0.03Cr, 0.01Ni, 0.02Cu, 0.03Al, 0.01N. Plates 20 mm thick were cut from the root surface into test pieces of 200 × 75 mm with water jet cutting machine, then processed to the desired roughness level with milling machine, and cleaned of the oxide layer by low-speed sand-blasting. The surface roughness of the joint edges was measured with the contact roughness measuring device Taylor–Hobson Surtronic 10 Ra, with a measuring range of 0.1–40 μm, according to EN 10049:2005 [25], rounded to the nearest standard value.

Two variants of the setup were used: butt joint and butt joint with a pre-set air gap. The carbon steel strip was used (Figure 2), and the width of the air gap was 0.2 mm.

The equipment setup was, as shown in Figure 3, with the laser welding head mounted on the positioning system. In all sets of experiments the steel specimens were tightly fixed flat on the jig. Argon (20 l/min flow rate) was used as a shielding gas, delivered to the weld through the MIG/MAG welding torch. The weld penetration levels and weld quality levels were investigated according to ISO 13919-1:1999 [26].

The experimental plan was divided into two sets. In the first set, St3 steel plates of $t$ = = 16 mm with roughness $Ra$ = 2 μm were welded at welding speed $v_w$ = 1–2 m/min, laser power $P_L$ = 12–14 kW and focal point position $f_{p.p}$ = –7.5 mm.

Two-level factorial design (edge surface roughness (numeric) and pre-set air gap (cate-

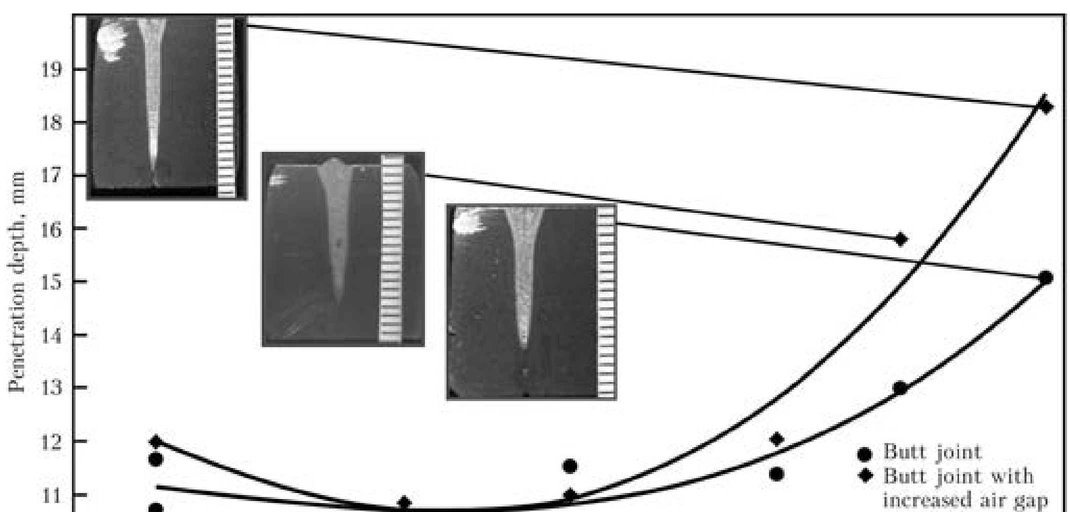


**Figure 5.** Depth of penetration of St3 steel 20 mm thick in laser welding at $P_L$ = 14 kW, $v_w$ = 2 m/min, $f_{p.p}$ = –7.5 mm, different roughness and air gap levels

goric)) was used in the second set of experiments on St3 steel plates 20 mm thick. Welding parameters were based on the results of the first set of experiments and remained constant ($v_w$ = = 2 m/min, $P_L$ = 14 kW, and $f_{p.p}$ = −7.5 mm).

**Results and discussion.** The results of the first set of experiments are shown in Figure 4. Interestingly, the additional gap increased the penetration depth significantly but caused an incompletely filled groove defect.

The results of the second set of experiments (Figure 5) show the minor changes in penetration depth or geometry shape of the weld at *Ra* = = 3.2–5.0 μm. Addition of the 0.2 mm steel strip to increase the gap between the plates does not change the trend at these roughness levels. At *Ra* = 5 μm an increase in the number of imperfections was recorded for the case of the pre-set air gap. Maximum penetration level of 15 mm was achieved with *Ra* = 6.3 μm. In combination with the 0.2 mm strip, the penetration depth increased to 18.3 mm. In both cases, the welds were of the confident stringent level for partial penetration with no critical imperfections.

### Conclusions

In butt joint laser beam welding of St3 structural steel at edge surface roughness from 2.0 to 6.3 μm, maximum penetration depths were achieved at *Ra* = 6.3 μm. Addition of the 0.2 mm stainless steel strip to increase the gap between the steel specimens gave a positive result at *Ra* = = 6.3 μm, namely penetration depth increased to 18.3 mm. At the other roughness levels tested, the additional gap did not cause any significant changes in the weld characteristics. These finding suggest several conclusions:

1. The observed increase in penetration depth at *Ra* = 6.3 μm with increased air gap may be explained by changes in the re-reflection patterns that cause an increase in the absorption at the edge surfaces. With further increase in the roughness level and air gap, significant part of the laser beam may «fall through» the gap, and the absorption decreases.

2. The influence of the edge surface roughness might vary during the welding process, as the material melts in front of the keyhole. It means that the edge preparation has significant influence on the process only during the keyhole initiation, when the first re-reflections take place as the edge surface roughness with the increased air gap changes the pattern of the re-reflections. Therefore the absorption increases, the initial keyhole becomes deeper and more stable, while during the process the effect is no longer critical.

Both optimum edge surface roughness levels and increased air gap between the plates in butt joint laser welding should be taken into account at the stage of product design. However, a number of important limitations need to be considered: the welding setups, equipment and materials used in the experiments. Based on current knowledge, further experimental investigations are needed to ascertain the phenomena underlying the correlation between absorptivity and roughness level. Pre-determined edge surface roughness may be used with pre-heating techniques to promote an additional increase in the absorption. The relationships and causalities of these factors require further investigation in future studies. The findings of this study support the development of clear recommendations for edge surface roughness in thick section welding with high power lasers.


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## *NEWS*

# *Procedure for Evaluation of Technical State and Technology for Repair of Load-Carrying Structures of Transport Vehicles*

It is a pressing problem to extend designed service life of transport vehicles. To solve it, it is necessary to estimate the actual technical state and residual life of load-carrying structures after they have exhausted their designed service life, and substantiate a package of the research, technical and organisational actions aimed at ensuring safe operation during the newly established service life. Statements and requirements were formulated for the scientific approach to ensuring safe operation of structures, based on the up-to-date notions of calculations and design, allowance for service loading and operating time of components, estimation of properties of materials, technical diagnostics, improvement of quality of the joints, application of new technological processes, including strengthening treatments.

Analysis of the technical state, actual operating time and service loading of load-carrying structures of the rolling stock makes it possible to establish types, causes and recurrence of premature damages, develop technical solutions for repair of the load-carrying structures with a 10–15 years extension of their designed rated service life, repair the load-carrying structures of an experimental batch of the train cars by extending their specified service life, develop a project of repair of the load-carrying structures of the inventory fleet of vehicles by the results of operation of the experimental batch of the cars, and train the Customer's staff in operating procedures.

The end product is a 10–15 years extension of the design service life of the rolling stock load-carrying structures, the cost of repair operations being no more than 40 % of the cost of a load-carrying structure.

In industrialised Western countries the problem of extension of life of the load-carrying structures is addressed, as a rule, through their reconstruction, and involves considerable expenses. Western Germany and USA pay attention to experimental-analytical estimation of the residual life of traction rolling stock and span structures of road bridges to plan their replacement and reconstruction.

In the solution suggested, estimation and guaranteed assurance of the residual safe operation of the load-carrying structures that have exhausted their design service life are a logical continuation of the development of the probability-statistical approach to fatigue calculation. This approach was developed in the 1980s of the last century by the E.O. Paton Electric Welding Institute and introduced in the 1990s into the design practice in the form of methodical guidelines of the USSR State Standard. It permits a differential allowance for the effect of factors of design embodiments of components and their service loading in calculation of the fatigue life of welded structures, and provides a substantial improvement of accuracy of the fatigue calculations. General provisions were worked out for the guaranteed residual safe operation and extension of lifetime of the load-carrying structures of subway cars, «Ukrzaliznytsya» traction rolling stock and industrial vehicles, allowing for probable upgrading and new criteria of the limiting state.

The guaranteed residual safe operation and extension of lifetime of the structures are provided through optimisation of the repair solutions, based on improvement of the calculation methods, use of the new, more substantiated criteria of the limiting state, and upgrading of assemblies by using the advanced technologies.