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The effect of joint edge surface preparation on the efficiency of fiber laser welding of low-alloyed steels

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1. Introduction

Applications for laser beam welding (LBW) have increased steadily in recent years because the many advantages of laser processing are being recognized and utilized to produce better products with greater productivity and at lower cost. Katayama et al. [1] highlighted that laser welding phenomena are satisfactorily understood and provided in-depth analysis of existing methods for deep penetration LBW.

Duley [2] compared laser beam welding and traditional welding process. LBW is more efficient due to higher welding speeds, lower heat input and better quality. Another important factor is material savings: in mass-production of parts with greater seam length (meters long) and high thickness (16-20 mm) with LBW there is no need for beveling or filling material in single-pass welding. These results are achieved with the use of a keyhole welding technology that provides high levels of weld shape factor, defined by the width to depth ratio. With traditional welding methods this factor is usually around 3:2 for good quality welds, while with LBW the factor can be 1:10, or even more narrow and deep, with acceptable beam quality.

Göbel et al. [3] investigated laser beam welding process and concluded that with the use of high power fiber lasers (HPFL) welding can be improved in terms of productivity, reduced heat input and reduced distortion.

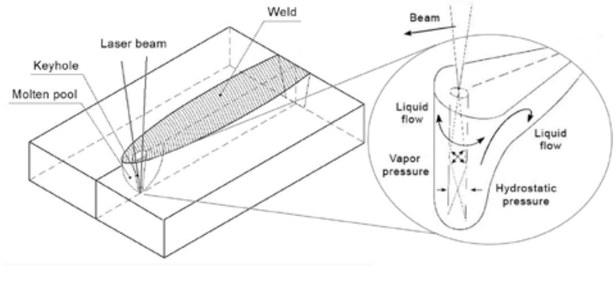


Fig. 1 Laser beam welding process [4]

The schematic view of LBW process in butt joint configuration is presented on Fig. 1. The main parameters of the LBW process are laser power L_P, welding speed v_W and focal point position in relation to the top surface of the welded joint *fpp*. Additional parameters include protection from oxidation (e.g. type of shielding gas used), edge surface preparation, use of filler materials, and preheating techniques or other methods to increase the effectiveness of penetration or improve metallurgical aspects. In analysis of existing applications by Quintio et al. [5], Katayama et al. [6], Katayama et al. [1] and research to date by Zhang et al. [7] were mentioned laser welding and it can be noticed that there is a tendency to focus on optimizing the laser and process parameters and relatively little attention has been paid to the physical parameters of material, like surface preparation of the joint edges.

Methods of improvement of laser beam welding efficiency with surface modifications have been discussed during last 40 years. Arata and Miyamoto in 1972 [8] investigated absorption characteristics of CO_2 laser beam in various conditions using a calorimeter. In 1988 according to their findings, absorption level has a tendency to increase with the surface roughness level until the surface melts and absorption decreases to constant level. Covelli et al. [9] studied laser beam welding of 4 mm stainless steel with a CO_2 4 kW laser and concluded that weld properties are not affected by the surface roughness. Ricciardi and Cantello [10] suggest using surface coatings to increase absorption during CO_2 laser processes.

Up to date research shows that with use of high power lasers, the surface roughness has a large effect on absorption, due to the multiple reflection undulations and is an important component of weld quality optimization, as it strongly modulates the local absorptivity during the laser welding process. Bergström et al. [11] recorded, by reflectance measurements, a trend of increasing absorption for increasing roughness above Ra 1.5 µm for stainless steels and above 6 µm for low alloyed steels. Kaplan [12] concluded that even a rather low level of roughness (of the order of 5–7 µm) strongly modulates the local absorptivity across the surface of molten metal. Sokolov et al. [13] using penetration depth and calorimeter absorbed energy measurements, a correlation between edge surface roughness and absorption in welding structural steel in a butt-joint setup was observed. The absorption of structural steels in butt joint laser welding has a significant dependence on the edge surface roughness at laser powers of ≥ 10 kW, as shown in Fig. 2.

Although the experimental data are uncontested, the mechanisms standing behind this correlation are not yet totally understood. In empirical experiments conducted thus far, the edge surface preparation was applied to the whole surface and the effect of varied or asymmetrical edge surface preparation was not investigated.

From a practical perspective, utilization of findings on the effect of edge surface preparation should not lead to additional costs when choosing manufacturing methods in accordance with the surface roughness they create. However, an increase in the number of processes required for edge surface preparation, like additional machining of the edge surface to create a required roughness level, would certainly decrease the economic benefits of using LBW. One hypothesis suggested by Sokolov et al. [13] claims that edge surface roughness has a critical effect on welding efficiency only at the very beginning of the process, when the keyhole is initiated, and that after stabilization of the keyhole it has no effect on the optical or absorption properties of the edge surface. If this is the case, machining need be applied only to part of the edge surface, which would result in considerable cost-savings in meters-long welds.

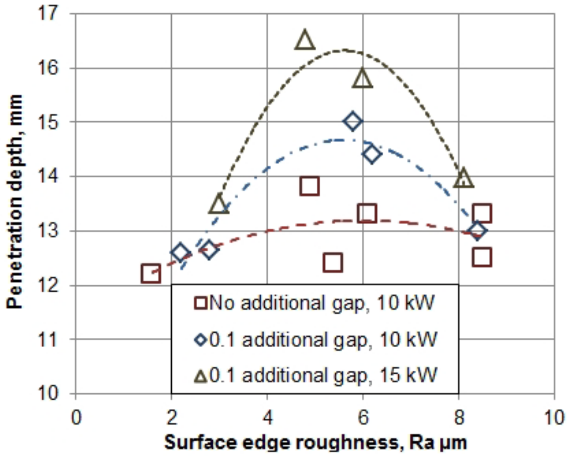


Fig. 2 Penetration depth at different roughness levels, low alloyed steel S355, thickness 20 mm, welding speed 2 m/min [13, 14]

The purpose of this paper is to evaluate and validate the effect of surface roughness variation along the joint. The results of this investigation provide initial indications of optimal edge surface preparations for laser welding and show whether the effect of surface roughness is critical only during the initial keyhole formation or throughout the whole welding process.

2. Experimental

Welding experiments with a high power fiber laser IPG YLR 10000 were performed on low alloyed steel S355 EN 10025: 2004 [15] plates. The nominal chemical analysis of the plates is shown in Table 1. Plates of 20 mm thickness were into test pieces of size 350 mm x 150 mm with a water-jet cutting machine and then processed to the desired roughness level with a milling machine or shot blasted. The surface roughness of the joint edges was measured with a contact roughness measuring device, Taylor-Hobson Surtronic 10 Ra, with a measuring range of 0.1-40 µm, according EN 10049: 2005 [16].

Table 1

Nominal chemical analysis and mechanical properties of S355

<table>
<tr><th colspan="6">Chemical composition, wt%</th></tr>
<tr><td>C</td><td>Si</td><td colspan="2">Mn</td><td>P</td><td>S</td></tr>
<tr><td>0.18</td><td>0.37</td><td colspan="2">1.39</td><td>0.02</td><td>0.01</td></tr>
<tr><td>Cr</td><td>Ni</td><td colspan="2">Cu</td><td>Al</td><td>N</td></tr>
<tr><td>0.03</td><td>0.01</td><td colspan="2">0.02</td><td>0.04</td><td>0.01</td></tr>
<tr><th colspan="6">Mechanical properties</th></tr>
<tr><td colspan="2">Yield strength, MPa</td><td colspan="2">Tensile strength, MPa</td><td colspan="2">Hardness, HV</td></tr>
<tr><td colspan="2">355</td><td colspan="2">470</td><td colspan="2">180</td></tr>
</table>

Four butt joint setup types were used to achieve constant or varied edge surface roughness in the weld:

- no machining: both edge surfaces of Ra 4.8 – 6.3 µm, shot blasted;
- full machining: both edge surfaces to constant roughness of Ra 6.3 µm ;
- partial machining: first 50 mm of the surface to Ra 6.3 µm and the remaining 300 mm to Ra 3.2 µm;
- combination of Type 1 and Type 3: one section is not machined, as in Type 1, and the second section is partly machined, as in Type 3. This setup is used to check the effect of asymmetrical edge surface preparation.

Types of setup are schematically shown in Fig. 3, numbered and color-coded for easier identification in further figures. Thin lines indicate the machining and numbers show average edge surface roughness in microns. No machining was used in setup Type 1: the edge surface was cleaned from the oxide layer by low-speed shot blasting with resulting average edge surface roughness from 4.8 to 6.3 µm.

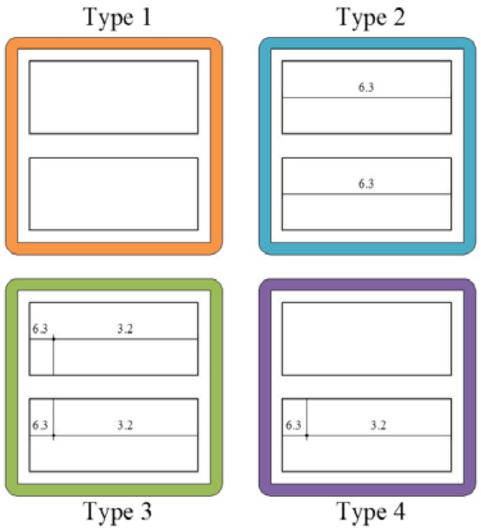


Fig. 3 Types of butt joint welding setups used in the experiments

Table 2

Process and optical parameters, fiber laser IPG YLR 10000

Process parameter	Units	Value
Laser power	kW	10
Welding speed	m/min	1.2
Focal point position	mm	-4
Shielding gas, flow	l/min	Argon, 20
Fiber core diameter	µm	200
Collimation lens focal length	mm	150
Focusing lens focal length	mm	300
Focal point diameter	µm	400

Single categorical factor randomized design with

4 repetition points was used: the only variable was the type of setup, total of 16 experiments Welding parameters were constant during all the experiments and are presented in Table 2.

Cross sectional cuts of the test welds were made at distances of 10, 175 and 340 mm from the starting point of each weld. The weld penetration depths and weld quality levels were investigated according to ISO 13919-1:1996 [17]. Hardness test procedure, shown in Fig. 4 was performed according to ISO 22826: 2005 [18].

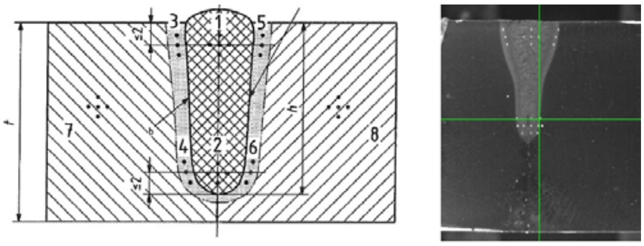


Fig. 4 Hardness tests procedure (left) and example of the tested sample (right)

Setups were compared on the following output parameters:

- penetration depth in mm;
- process stability: the standard deviation of the penetration depth results;
- weld quality: quality of level for partial penetration welds [17];
- hardness.

3. Results and discussion

3.1. Penetration depth

The results of all the experiments are shown in Fig. 5. Mean and standard deviation for penetration depth at cross-sectional cut distances are presented. To improve visualization of the data, the plot is divided into two parts: the upper graph presents Type 1 and Type 2, i.e. results for constant edge roughness level, and the lower graph shows Type 3 and 4, i.e. results for varied edge surface roughness level.

3.2. Quality analysis

Type 1 gave better results than the other setups: deeper penetration and higher weld quality as can be seen from Fig. 6, and this setup is the easiest to produce, as there is no machining, only low-speed shot blasting (Fig. 7).

Type 2 showed higher process stability than the other setups. However, quality analysis revealed hot cracks and other defects at all distances. In other setups, macrographs showed that the welds were of level B or C quality at the distances of 10 and 175 mm from the beginning of the weld and that the hot cracks have tendency to appear at the distance of 340 mm.

Type 3, with varied edge surface roughness, gave results of worse quality than Type 1 and type 2. It seems that the air gap volume change caused by the change in the edge surface roughness disturbs the keyhole, which in turn results in a decrease in penetration depth, stability and quality of the weld.

Type 4 gave a deeper penetration weld and higher process stability than Type 3, probably due to the reduction of the air gap volume change.

Overall quality analysis is shown in Fig. 6. Macrosection examples for each setup type are shown in Fig. 8.

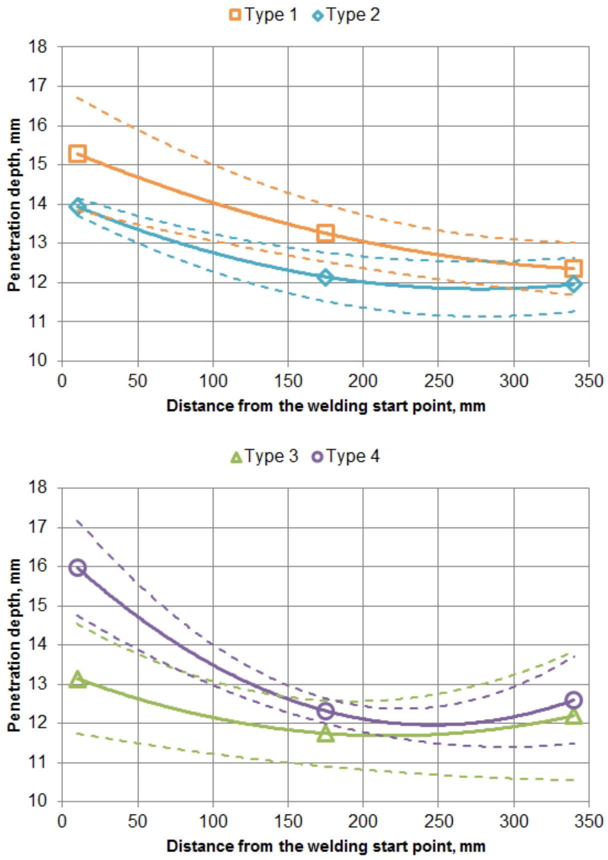


Fig. 5 Change of the average depth of penetration along the weld seam (solid lines) and 95% confidence interval (dotted lines)

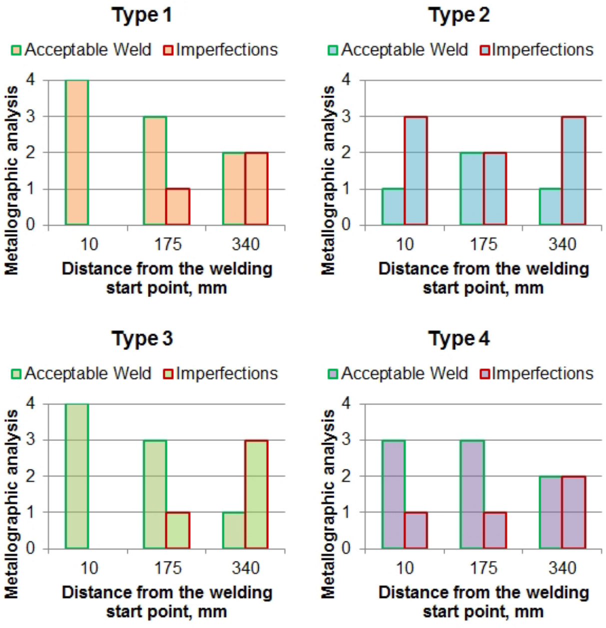


Fig. 6 Quality analysis by setup type and distance from the weld start

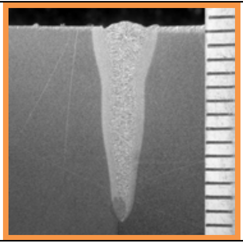
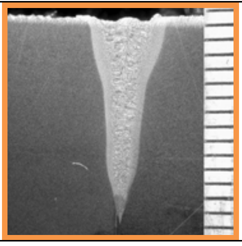
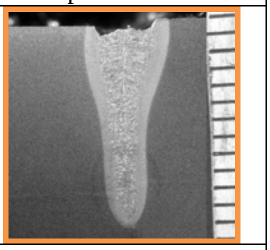
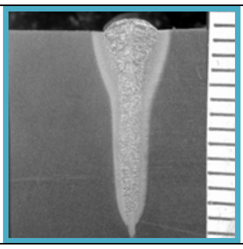
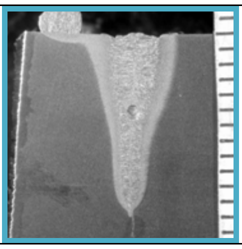
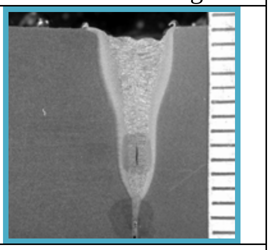
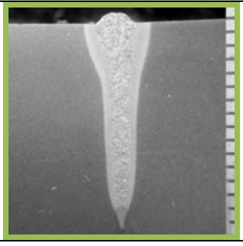
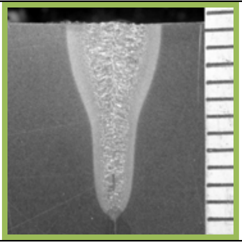
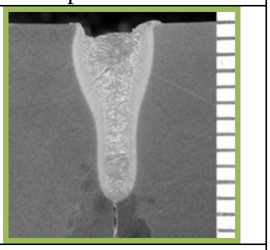
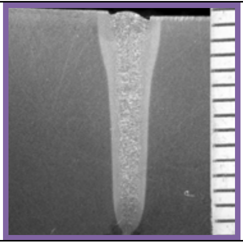
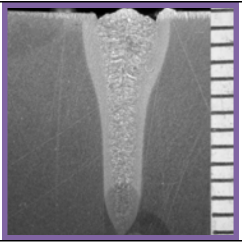
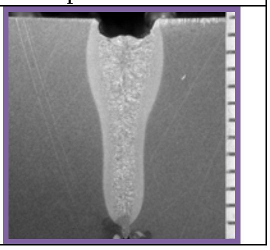
Comments, Type 1	10 mm from start point 14 mm penetration acceptable: B level	150 mm from start point 13.7 mm penetration acceptable: B level	340 mm from start point 12.4 mm penetration acceptable: B level
Macrosection, Type 1			
Comments, Type 2	10 mm from start point 14 mm penetration acceptable: B level	150 mm from start point 12.4 mm penetration Non acceptable: Pore Ø 1 mm	340 mm from start point 13 mm penetration Non acceptable: Crack 1 mm length
Macrosection, Type 2			
Comments, Type 3	10 mm from start point 14.8 mm penetration acceptable: B level	150 mm from start point 11.2 mm penetration acceptable: B level	340 mm from start point 11.36 mm penetration acceptable: C level
Macrosection, Type 3			
Comments, Type 4	10 mm from start point 14 mm penetration acceptable: B level	150 mm from start point 13.7 mm penetration acceptable: B level	340 mm from start point 12.4 mm penetration acceptable: D level
Macrosection, Type 4			

Fig. 7 Macrographs of weld samples at different setup types and different distance from the welding start point

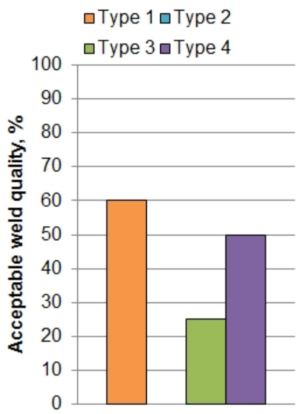


Fig. 8 Overall quality analysis by setup type

3.3. Hardness tests

Hardness tests were performed in accordance with ISO 22826, 2005 as shown on Fig. 4. Comparison of hardness tests results shows that with increase in penetration depth a significant increase in fusion zone (FZ) hardness (up to 350 HV5) and relatively small decrease in heat-affected zone (HAZ) hardness (up to 250 HV5). Base material hardness level is 140-170 HV5.

Correlation between maximum hardness and set-up type is shown on Fig. 9. A small increase in hardness level was noticed in setup Type 2 while hardness in other setups was on approximately same level, expected for 1 m/min welding speed and reported by Sokolov et al. [19].

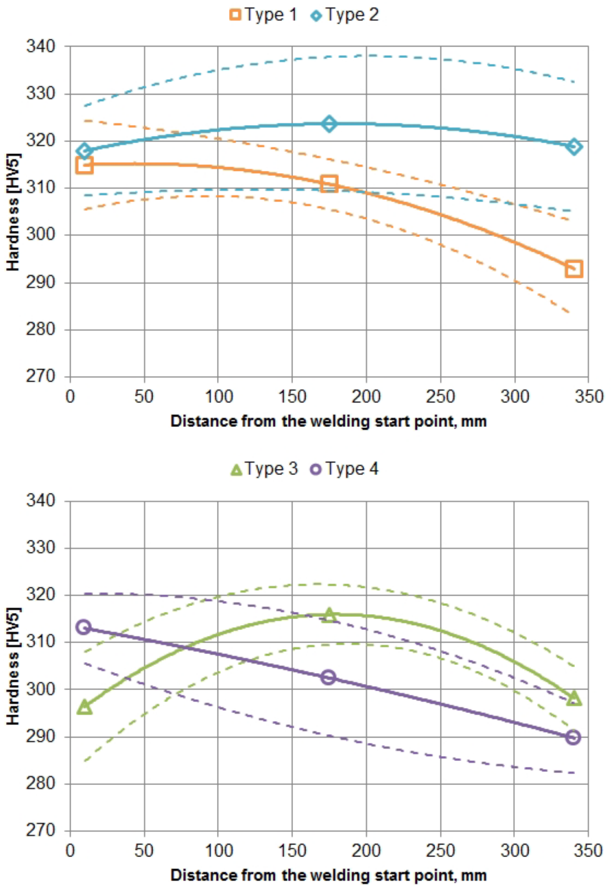


Fig. 9 Change of the maximum hardness along the weld seam (solid lines) and 90% confidence interval (dotted lines)

3.4. Evaluation

Type 1 was considered to be the most appropriate choice for the laser beam butt joint welding of S355 structural steel. This finding corroborates the ideas of Salminen et al. [20], who concluded that an abrasive water jet cut joint edge gives deeper penetration with the same line energy compared with a machined joint edge and that too high quality a joint edge can decrease the penetration depth in high power laser welding.

On the basis of the author's previous research [13, 14] it is possible to hypothesize that Type 1 setup will be the most appropriate choice in setups with a pre-set air gap, and Type 1 setups will show deeper penetration than achieved in the presented experimental set with 0.05-0.1 mm increased air gap at the same process parameters. Surprisingly, Type 4 was found to be on the second by penetration depth and weld quality.

Returning to the hypothesis posed at the beginning of this study, it is now possible to state that set-up with constant roughness level among the edge length gives more stable process with deeper penetration depth and higher stability than welding process with varied edge surface roughness. Taken together, these results suggest that for increase of the efficiency of laser beam welding process through edge surface modification, edge surface parameters are recommended to be constant among the whole length of the edge.

Modifying surface roughness to improve energy absorption and welding efficiency should not incur additional costs as many manufacturing methods are available and an appropriate method can be selected in accordance with the desired surface roughness.

4. Conclusions

In butt joint laser welding of S355 steel of 20 mm thickness at constant welding parameters a comparison of four butt joint set-ups was performed. Taken together, these results suggest that in order to achieve higher productivity of laser beam welding of butt joints of structural steel, the joint edge manufacture should be prepared with an abrasive water jet cut, shot blasted, and should exhibit a preferable edge surface roughness close to 6.3 µm.

Current standards and recommendations for the laser beam welding are based on idea that identically polished edge surfaces without variations in the roughness and without any gap between the plates is the best setup in butt joint welding. Such limitations certainly reduces the sector of possible applications for laser beam welding due to necessary additional accurate machining to Ra 0.4-1.6 µm and zero gap tolerance. The results of the research show that even with unequal and varied edge surface preparation non-constant edge surface roughness and gap of 100-150 µm produce acceptable welds. Further investigation is required for validation and more accurate investigation of the phenomenon.

These empirical findings provide further support for the hypothesis that edge surface topology is an important factor to be taken into account at the stage of product design for laser beam welding.

It is, however, important to recognize the limitations of the findings of this study; namely, the process parameters (welding speed, power level, focal point position), optical parameters (focusing lens focal length, focal point diameter) and the materials (S355 low-alloyed steel) used in the experiments. Based on current knowledge, further experimental investigations are needed to ascertain the phenomena underlying these results. Investigation of the correlation between edge surface preparation methods and weld quality in welding of other materials is recommended.

Acknowledgments

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THE EFFECT OF JOINT PREPARATION ON THE EFFICIENCY OF FIBER LASER WELDING OF LOW-ALLOYED STEELS

Summary

The paper studies the effect of butt joint edge surface preparation on welding efficiency of low-alloyed steel S355 of 20 mm thickness. Welding was performed with a high power fiber laser with a wavelength of 1070 nm at power level 10 kW. The quality of edge surface machining and post-processing was varied in the experiments. Based on the results, recommendations for edge surface preparation for butt joint laser welding are presented. The investigation shows that to achieve higher productivity in laser beam welding of butt joints of structural steel, the joint edge preparation should be carried out with an abrasive water jet cutting followed with shot blasting, and should exhibit a preferable edge surface roughness close to 6.3 μm.

Keywords: Laser welding, low-alloyed steel; butt joint; edge preparation.

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