https://doi.org/10.37434/tpwj2021.05.02

IMPROVING THE EFFICIENCY OF ROBOTIC FABRICATION OF STEEL TRUSS WELDED STRUCTURES

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It is shown that to increase the productivity of robotic fabrication of fragments of steel truss RHS (Rectangular Hollow Section) structures it is advisable to make workpieces by precision laser cutting with subsequent assembly of fragments by spot tack welds and consumable-arc seam welding with current-carrying (hot) filler wire. Laser cutting with radiation power of ~1.0 kW and compressed air blowing at the pressure of 1.5 MPa allows obtaining ready for further welding elements of RHS structures with the accuracy of 0–0.1 mm. It is established that in the case of application of consumable-arc welding with hot filler wire, the speed increases by ~1.5 times compared to conventional consumable-arc welding. 13 Ref., 6 Figures.

Keywords: laser cutting, welding, consumable electrode arc, current-carrying filler wire, fillet joints, carbon steel, structures

Structural advantages of tubular steel elements have become more and more obvious during the last decades owing to investigations and experience in construction [1, 2]. These elements are often used all over the world, particularly in large-span structures. For instance, the first all-welded tubular truss structure of a bridge without supports or connections, was recently commissioned in the Germany. It is an innovation in bridge-building as an integral structure and is an advanced bridge structure as a whole [3]. The truss girders were earlier made from angle-type members, connected into nodes by welded on gussets. In the XXI century new design solutions for truss structures appeared in industry, which include, first of all, use of CHS (Circular Hollow Sections) and RHS (Rectangular Hollow Sections) elements joined by welding directly in the abutment points around the contour [4, 5].

It is known that the elements of hollow structural sections (HSS) have many advantages over the equivalent sections with an open cross-section, including better torsion resistance, as well as tensile and compressive loading, aesthetic character and saving in terms of material costs [5]. At first glance HSS elements can be rather easily joined, having cut the edges and welding them to each other. However, depending on the configuration of the joint connection and number of connected members, it may lead to producing complex and expensive structures.

In order to reduce the costs and accelerate fabrication of such structures, it is rational to divide them into individual assemblies, which can be welded by industrial robots [6]. In the actual process of truss structure fabrication the elements are usually joined by spot welding on a mounting platform, and then welded entirely in robotic sections [7]. However, this leads to a number of problems, related to preparation and performance of welding.

Robotic welding requires greater adherence to the geometrical dimensions of parts to be welded [8]. This primarily applies to uneven gaps, caused by inaccurate set up, i.e. cutting of the parts for welding. As a rule, cutting is performed by mechanical method using saws. Here, the geometrical dimensions of the parts can change, because of wear of the saw surface. More over, cutting is performed, mainly, in semi-automatic machine tools, so that the human factor is added to the accuracy problems. Another problem is the impossibility of obtaining curvilinear shapes of the cut surfaces by saw cutting. This peculiarity leads to appearance of gaps in the butt joint assembled for welding, so that it does not completely meet the requirements of optimum (no gap) assembly. This problem can be solved either by application of certain techniques, or addi-

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tional milling for optimum assembly of the joint for welding. In both the cases, the productivity decreases, while the cost of work performance rises.

Laser technologies are the most promising for preparation of billets with the required geometry of the cut surface [9]. In particular, rather widespread is the process of laser cutting, using industrial robots [10]. At up to 6 mm thicknesses the laser beam ensures a thin (up to 0.5 mm) cut. It enables greatly reducing the metal consumption in cutting, as the width of mechanical CNC cut at up to 6 mm thickness usually is up to 5 mm. [11]. More over, the affordability of modern laser equipment is gradually becoming closer to that of CNC machine tools. Compared to plasma cutting, at laser process a smaller number of working tool parts (primarily cutting nozzles) are consumed, and no finishing of the edges is required for further welding [10]. Use of a robot enables making cuts with complex paths in space, which are required to produce the welded joint in terms of its produceability and strength, and also promotes the flexibility of its transition from fillet to butt joints.

In order to produce steel structures from CHS and RHS using robots, more rational and adaptable-to-fabrication is the method of consumable electrode pulsed-arc welding in a mixture of gases (GMAW-P) [12]. Nonetheless, this welding method has certain features, which do not always have a positive impact on the welding process. One of the methods to improve the process of consumable electrode pulsed-arc welding is additional application of filler wire. It enables increasing the amount of metal during welding without raising the welding current. More over, to increase the effectiveness of welded joint formation when making the fillet welds, it is rational to apply additional filler wire preheated by electric current of different polarity [13]. Such a combination of consumable electrode and additional heated wire enables a certain increase of the speed of welding the fillet welds without increasing the current of the consumable electrode arc, improving the geometry of the weld surface due to reduction or complete elimination of undercuts, reduction of the structure deformation through reducing the heat input at preservation of the amount of metal, involved in weld formation. Moreover, such an approach with application of additional filler wire will allow improvement of the currently available robotic complexes for consumable electrode welding with minimum capital expenditures.

Thus, improvement of the effectiveness of fabrication of truss welded structures from CHS and RHS pipes requires application of a complex approach, which will consist in using the robotic laser cutting of billets from steel shaped pipes and consumable electrode robotic welding with additional heated filler wire.

The objective of the work is increase of the effectiveness of robotic manufacture of fragments of steel truss structures due to application of precision laser cutting of billets with further preparation and consumable-arc welding.

This objective was reached by solving the following task: optimization of the technology of precision laser cutting of carbon steels up to 6 mm thick; preparation of cut billets for consumable-arc robotic welding; consumable-arc robotic welding, also with additional current-carrying (hot) filler wire.

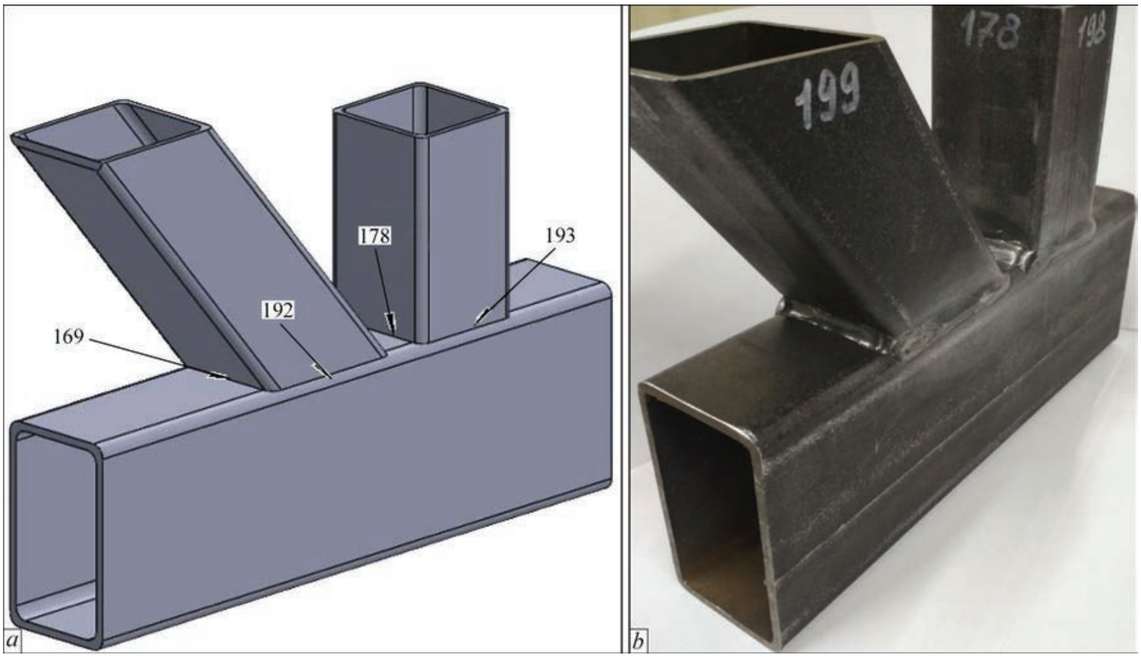

Figure 1. Appearance of an assembly of a truss structure from RHS elements: *a* — model with spatial arrangement of welds; *b* — welded fragment

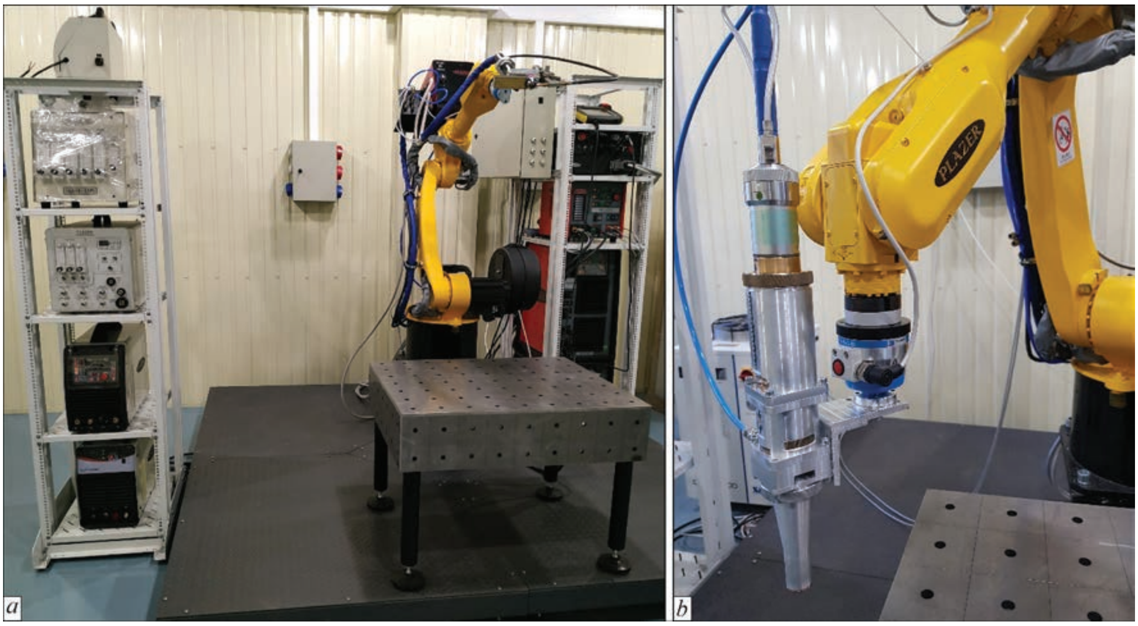

Figure 2. Appearance of a laboratory robotic complex (*a*) and head for laser cutting (*b*) in the robot arm

The assemblies of truss RHS structures were made from shaped pipe of 60×60 and 120×60 mm size with up to 6 mm wall thickness (Figure 1). Laser cutting was used to make from this pipe 50–300 mm long fragments with square and bevelled edges. Pipe material is Q235 carbon steel (steel St3 analog). This steel is not prone to hot or cold cracking during GMAW, so that the structure does not require heating or monitoring of the cooling rate after welding. Welding experiments were performed using electrode and filler wires of ER-70S grade (Sv-08G2S analog) of 1.0–1.6 mm diameter.

In order to conduct technology studies, a robotic laboratory complex was developed (Figure 2), which includes fiber laser of MFSC-1000 model (MAX Company, PRC) of up to 1.0 kW power, Plazer R1 industrial robot of ingenuous design with arm radius of up to 1400 mm and lifting capacity of up to 10 kg; GMAW power source of Fronius TPS 450 model, power source of EWM Tetrix 421 AC/DC model for filler wire heating; gas treatment station, welding heads, welding table, welding-assembly fixtures, etc.

The need to apply precision laser cutting was related to the fact that usually at preassembly of the truss structure components time was consumed in the preparation section for manual fitting of the parts, which became necessary because of noncompliance with the dimensions of manufacturing the parts. Increase of the accuracy of parts manufacturing up to ±0.1 mm eliminated this problem.

Laser cutting head of our own design (Figure 2, *b*) was used to conduct a series of experiments on cutting carbon steel sheets, as well as shaped steel pipes (Q235 type steel) with wall thickness $\delta \leq 6$ mm. The best results were obtained in the case of application of compressed air with approximately 1.5 MPa pressure at deepening of the focus for ~1 mm under the surface of the material being cut, and not more than 1.0 mm distance between this surface and cutting nozzle edge. At approximately 1.0 kW power of laser radiation the cutting speed decreased from 240 to 60 m/h at increase of sheet thickness from 2.0 to 6.0 mm. The cut width was ~0.3 mm, the edges were smooth enough, and a small amount of flash was observed, which was quite easy to separate (Figure 3). The respective shaped pipes were used to cut out the required number of parts for further welding. The accuracy of their preparation was 0–0.1mm that satisfied the requirements to preassembly of truss structure components.

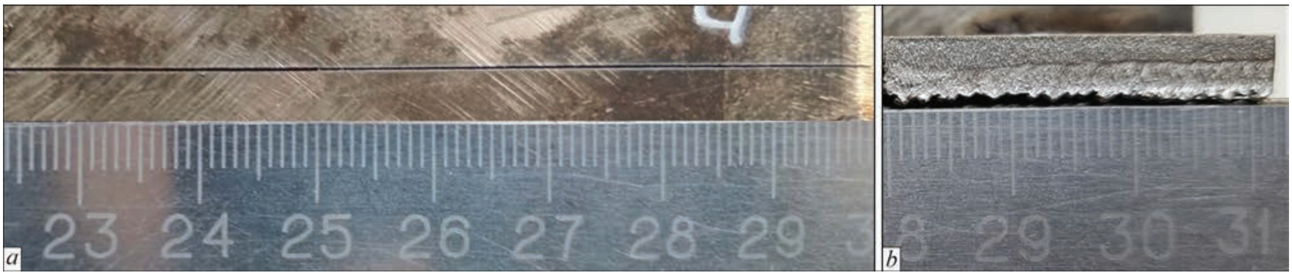

Figure 3. Width (*a*) and edge (*b*) of a laser cut of shaped pipe from steel of Q235 type (5 mm wall thickness)

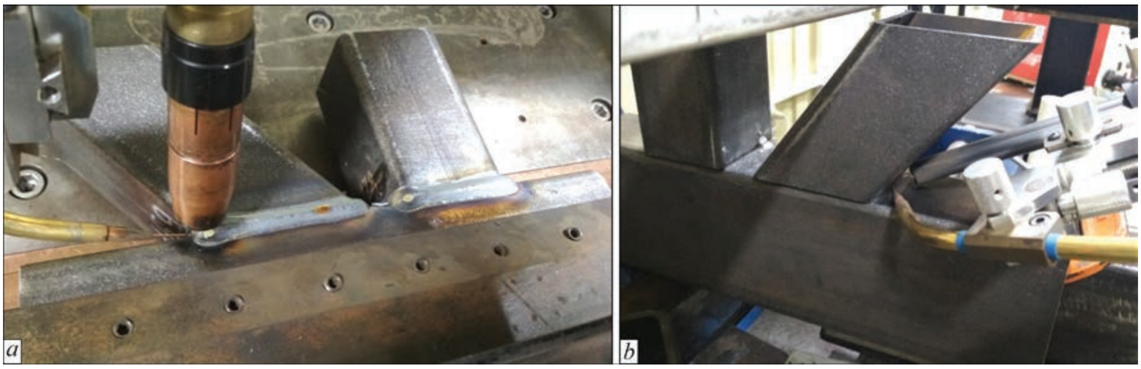

Figure 4. Application of a standard torch (*a*) and modified torch with narrowed nozzle part (*b*) for welding the truss structure assembly

The next stage was acceleration of preparation of the cut billets for robotic welding. The main problem which arose at this stage was time consumption for the process of structure assembly, its clamping and disassembly of the clamping devices in the robotic welding section, because of the presence of screw clamps in the structure. In order to eliminate this deficiency, it was proposed to transfer to the robotic welding section the structural elements preassembled by spot welding. With this purpose, PWI developed a project of a section of assembly for welding with all-purpose welding-assembly equipment and respective technology of making the assembly spot welds. The design of simplified fixture for fast fixation of the truss structure part preassembled for welding was developed for the robotic welding section. Such a type of clamping devices was selected, which ensure the minimum time for mounting the billet and its release after spot welding.

The last task, which was addressed within the framework of this study, was consumable-arc robotic welding (GMAW). The first important problem, which was solved here, was caused by the presence of rounding-off radius in the fillet zones of shaped pipe surface, which led to formation of a gap (1.0–1.2 mm) at abutment of the respective elements of the truss structure assembly. The second problem was related to the impossibility of welding with normal electrode extensions (12–16 mm), because of the close arrangement of the structural elements and large diameter of protective nozzle of the standard soldering iron, which did not provide access to 12–16 mm distance from the welding zone (Figure 4, *a*). The third problem concerned the need for welding in different positions in space, as the welded fragment of the truss structure was stationary, while the GMAW torch in the robot arm moved at different angles of inclination by a complex path.

The first of the above problems was eliminated by inclination of the torch axis at 20° angle relative to the conditional plane, which passes through the butt axis normal to the plane of the parts being welded. In order to enable performance of consumable electrode welding in difficult-of-access places with normal electrode extension (12–16 mm), a modified torch was developed and applied. It has a narrowed nozzle part, which can ensure welding performance at the distance of the order of 13–14 mm between the side walls (Figure 4, *b*). The third problem was eliminated by applying adaptive control of welding current, depending on the direction of movement in space: in the case of uphill welding the current was somewhat reduced, at downhill welding it was somewhat increased. Such a schematic of robotic welding is urgent to manufacture truss structures from steel RHS pipes, but to a greater extent — for structures from CHS pipes, as in the case of welding of one round pipe into another one the torch has to be moved by a saddlelike path.

The robotic experimental complex was used to perform the technological studies of welding the earlier cut by the laser method elements of shaped pipes from steel Q235 with $\delta = 4$ mm wall thickness with shielding by a gas mixture of 82 % Ar + 18 % CO_2. GMAW welding was used to make butt and tee (fillet) joints at shielding gas consumption of approximately 20 l/min. Investigations were conducted both for the case of the conventional GMAW, and with additional filler wire (Figure 4). Additional wire was fed backwards in the direction of motion (welding) with shifting relative to the electrode forward in the direction of motion to 2–5 mm distance. The wire was fed both without heating, and with heating. Here, both direct and different polarity current was used for heating. Direct current promoted the welding arc deflection and impaired the welding result. For this reason, symmetrical different-polarity pulses were used for heating of additional filler wire, with current $I_{HW} = 50–100$ A at voltage $U_{HW} = 10–15$ V, and electric power was in the range from 500 up to 1500 W at frequencies from 75 to 100 Hz.

First, the mode of conventional GMAW at the speed of 27–30 m/h was selected by the criterion of formation of sound welds without undercuts. Studies showed that in this case penetration of the welded

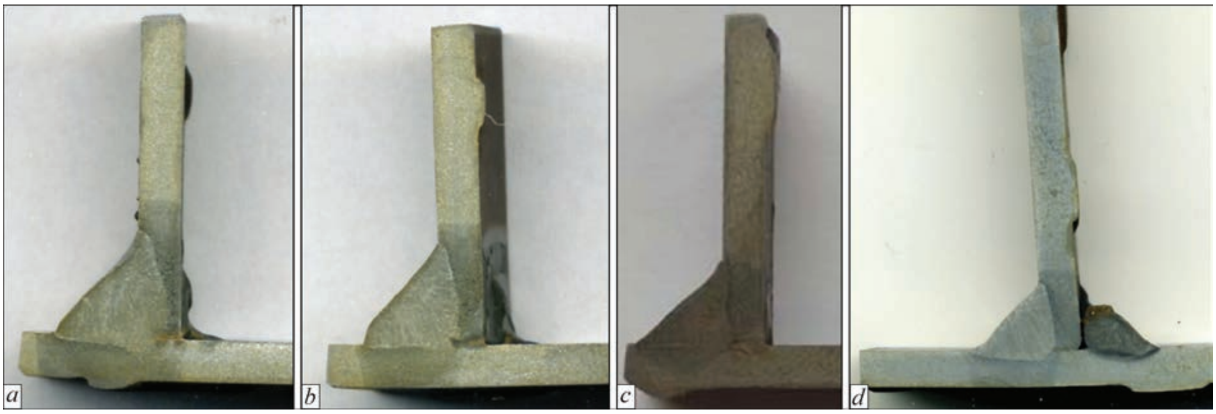

Figure 5. Macrostructure of samples with transverse cross-section of fillet welds (left) produced on assembled using tack welds (right) samples from Q235 steel (δ = 4 mm): *a* — GMAW without filler; *b*, *c* — GMAW with cold filler; *d* — GMAW with hot filler

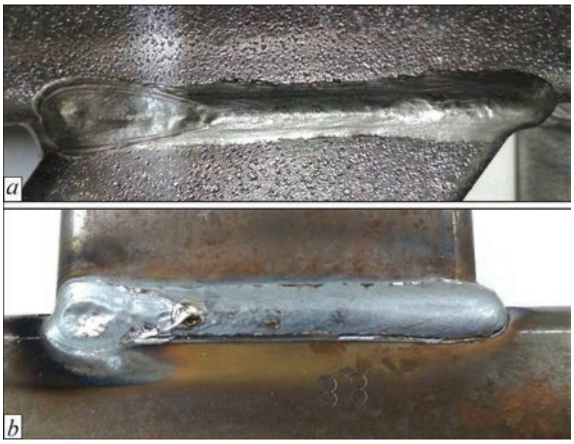

Figure 6. Appearance of welds, produced on samples of an assembly of a truss structure from RHS elements (Q235 steel): *a* — conventional GMAW; *b* — GMAW with hot filler

part wall was equal to about 50 % of the thickness (Figure 5, *a*). In order to raise the welding productivity, the welding speed was increased by 40 % with simultaneous increase of welding current. However, weld formation was considerably impaired, and undercuts appeared. Therefore, the speed was reduced to the initial value, and at the same time filler wire was added. Weld formation became satisfactory, but penetration decreased (to 10–20 % of the wall thickness), and productivity increased (Figure 5, *b*). In the case of an attempt to increase the welding speed by 40–50 %, lack-of-fusion of the weld metal with the base metal was observed (Figure 5, *c*). Introduction of filler wire heating promoted formation of sound welds without undercuts with satisfactory (not less than 30 %) penetration depth of base metal wall (Figure 5, *d*). Here, the welding speed increased up to 1.5 times, compared to conventional GMAW.

Analysis of the produced joints by such indices as weld formation and their strength, showed that conventional GMAW and GMAW with additional conductive (hot) wire are approximately on the same level. However, besides productivity, GMAW with hot wire features lower spatter and approximately 25 % shorter weld pool (Figure 6).

Conclusions

1. To increase the productivity of robotic manufacture of fragments of truss structures from steel RHS pipes, it was proposed to produce billets by precision laser cutting with further assembly of fragments by spot tack and consumable-arc seam welding with current-carrying (hot) filler wire.

2. Laser cutting with radiation power of ~1.0 kW and blowing compressed air at the pressure of 1.5 MPa allows producing ready for welding RHS structure elements with the accuracy of 0–0.1 mm. Here, 2.0–6.0 mm thick walls were cut at the speed of 240–60 m/h, and the cut width was ~0.3 mm.

3. For robotic fabrication of truss structures from steel CHS and RHS pipes a scheme was developed for welding the stationary fragments of such structures by a torch, which is moved by the robot arm in different positions in space. It differs by adaptive control of welding current, depending on the spatial position of the torch with feeding of hot filler wire backwards in the direction of welding.

4. To perform consumable-arc welding with hot filler wire, a specialized torch (narrower nozzle) was developed that enables welding in difficult-of-access places with normal electrode extension (12–16 mm) at 13–14 mm distance between the side walls.

5. It was established that in the case of application of consumable-arc welding with hot filler wire the speed rises by ~1.5 times, compared to conventional consumable-arc welding. Here, it is rational to apply symmetrical different-polarity current pulses of 500–1500 W power with 75–100 Hz frequency for wire heating.

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Received 26.04.2021