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A study on use of wobble features in laser welding of low alloy steel joint with butt joint configuration

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Abstract. Laser welding is modern digital welding process, which thanks to several advantages over traditional welding processes, is gaining ever growing role in manufacturing. The process has still some weaknesses. The better the beam quality the smaller the focal point, the actual welding tool, diameter is. Typically, because of this the welding of joints with lesser quality e.g. larger air gap is difficult or even impossible. So-called beam manipulation opens opportunities to deal with the problem. The dynamic beam manipulation gives opportunities to control the weld dimensions during the welding process by the requirements of individual locations of weld joint. This study used the two dimensional scanner to manipulate beam during welding with so called wobble function. Four different wobble configurations were tested in welding of low-alloyed steel with different joint qualities. The wobble typically made the welds wider, provided typically higher heat input and thus lowered the hardness of the joint. Wobble increased typically the root quality, but there are differences between different wobble parameters. It was possible to weld joints with wider air gaps in the selected material thickness, but the wider air gap and wobble caused finally, when wide enough the sagging of the joint.

1. Introduction

1.1. Laser welding production case

Machine Technology Center Turku Ltd (MTC) has been laser welding of special dimension rectangular hollow section steel beams for maritime industry for several years. These steel beams are used in cruise ship staircase construction as sidewall beams, and are later GMAW-welded together with steps, painted and installed to the ship blocks by the Turku shipyard's subcontractors (Fig.1 and 2). About 2000 beams have been laser welded to the nine different cruise ships during the years.


Fig. 1 and 2. Staircases under installation in Meyer Turku shipyard.

These steel beams are normally laser welded longitudinally from two C-shape press brake bended plates in horizontal position (PC) one side at the time, in butt joint configuration, as shown in Fig.3. Steel beams are typically from 2 m to 4 m long. At the ends there is typically also added separate bended parts in different angles. These parts are also laser welded together longitudinally and with the long parts crosswise. Special jigs are designed and build to use in laser welding to press these C-shape plates together during laser welding. Pressing force is carried out with pneumatic system.

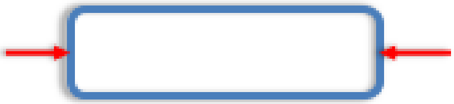

Fig. 3. Horizontal laser welding position.

Regardless that this laser welding production case has been going on several years, there is still some principal problems in it. MTC's large robotized laser welding system has no seam tracking system, which is normally crucial to any large laser welding work stations. Part preparation or setting into fixtures can be incomplete in different ways, e.g. poor laser cut quality, large air gap, linear misalignment. These shortages in production causes unnecessary trouble, time consuming corrections and unnecessary excessive heat input to the work piece. Therefore new laser welding techniques are always under observation in MTC to make production easier and quality better.

1.2. Laser welding with beam manipulation technique

A major improvement to original welding was achieved by manipulation of the focal point size. Using longer 500 mm focal length in existing ordinary laser welding head (Precitec YW52) has given more tolerance for the welding set up and eased the suitability of the large laser welding robot system in accuracy vice compared to the formerly used 300 mm focal length. This is realized by the larger focal point diameter. Diameter with used optical setup is changed to 1.0 mm from previous 0.6 mm. This has helped to achieve satisfying weld quality more easily.

Anyway, this relatively new laser welding technique to use dynamic beam manipulation, or beam oscillation, seems to be very interesting and promising technique to check out and to solve or at least to relieve these problems mentioned in chapter 1.1. The technique has been used e.g. to change the phase balance in welding of duplex stainless steel [1].

In Turku University of Applied Science's research investment program invested to the new laser welding head with beam oscillation, so called wobble head. Public tendering and purchase were done in 2020 and winter 2021 new “wobble head” was installed to the MTC’s large robot welding cell. Together with University of Turku and Turku University of Applied Science, MTC is now studying the use of different wobble functions and parameters to achieve better welds, more easily, compared to the stable laser welding head, generally and specially in this steel beam production case. This study is one of the first test trials done with this new welding head in MTC.

New IPG FLWO D50 wobble head is also additionally equipped with IPG LDD-700 Inline Coherent Imaging (ICI) sensor system, which can be used e.g. as a seam tracking system, keyhole depth measuring system and weld bead profile measuring system. These features were not examined in this study.

Some test welds were also videotaped with Cavitar C300 welding camera, which was purchased to MTC in Interreg Baltic Sea Region program INforM project. These videos were not precisely examined in this study. However, welding camera and ICI -sensor system will open up lot of possibilities for further research studies.

Fig. 4. IPG FLWO D50 wobble head with LDD-700 sensor system.

2. Test material

Test materials are taken from actual production steel plates, which have been delivered by the customer. Flat plate test material pieces are cut out from several C-shaped press brake bended production parts. Test piece edges were laser cut like in the normal production parts also

Material is hot rolled fine grain steel S355MC according to the standard EN 10149-2 [2] of thickness 4 mm. The nominal chemical and mechanical properties of the steel are given in Tables 1

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and 2, based on steel manufacturer test report (EN 10204 – 3.1) [3] of the melt analysis and mechanical tests of the cast of the test material. Mechanical properties represent the thermomechanically treated (TM) and pickled condition.

Tab. 1. Chemical properties of S355MC. [3]

	C	Si	Mn	P	S	Al	Nb	V	Ti
%	0.064	0.01	0.72	0.008	0.005	0.034	0.027	0.008	0.001

The carbon equivalent (Ceq) of the steel is 0.20 (Ceq = C+Mn/6+(Cr+Mo+V)/5+(Ni+Cu)/15).

Tab. 2. Mechanical properties of S355MC. [3]

Tensile test		
RP0,2 (MPa)	RM (MPa)	A (%)
418	479	33

Because the test plate materials were cut out of the actual left-over work pieces, the dimensions were not according to standard size welding procedure test plate (e.g. 350x150mm), but only about 250mm long.

3. Laser welding equipment

10kW IPG YLS 10000 fiber laser with four way beam switch was used in laser welding. Linear test welding lines were performed with industrial 6-axis Yaskawa Motoman UR50 –robot.

IPG FLWO D50 wobble head was used with 400 mm focal length and 150 mm collimation length. Connected process fiber has a diameter of 300 µm. Theoretical focal spot diameter is then 800 µm, which was also tested with Primes FocusMonitor - laser beam focus measurement system at 5kW laser power, see figure 5 for details. Focal lens is protected with cover slide window and with air knife, also additional air knife pipe was added to the welding head to cut the metal vapor movement towards welding head and to keep the optics clean from the welding spatter and fume. Additional air knife pipe was installed about 5cm above welding spot.

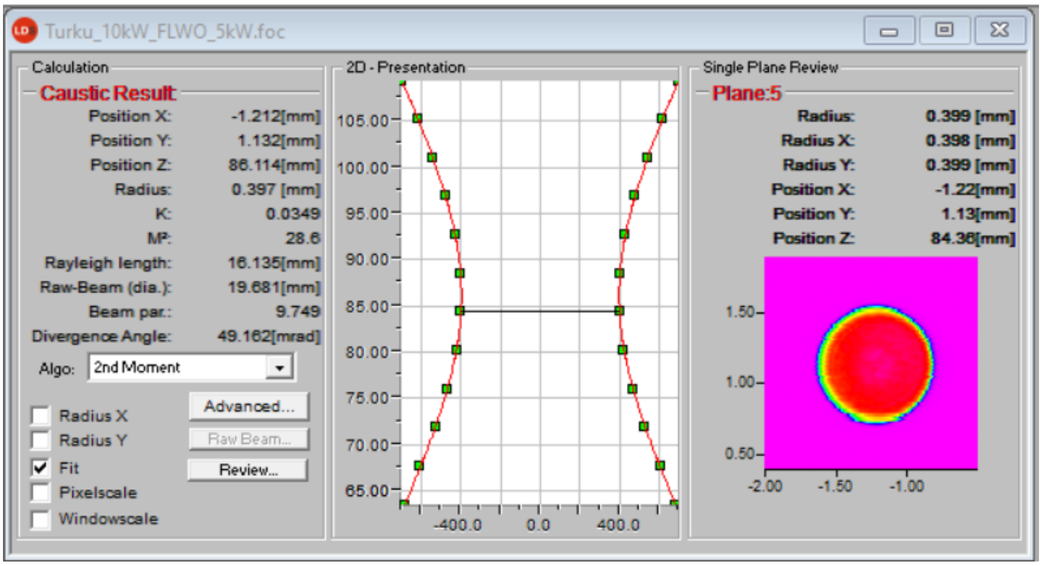

Fig. 5. Result of the focal spot measurement.

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4. Laser welding parameters
Main laser welding parameters were kept constant and only some wobble function parameters were varied during test welds. Tested wobble oscillation modes were selected from the basic electric waveform controlled functions of the wobble controller based on previous general laser welding experience. Butt joint I-groove test pieces were laser tack welded with nominal zero air gap.

4.1. Constant test parameters
Laser power and welding speed were kept constant in every test run, 5.7kW and 2.1 m/min were used. No shielding gas or no root gas was used. Focal spot vertical position was at the top surface of the plate, ±0mm. Focal spot horizontal position, and wobble oscillation movement center, was in the middle of the joint, as illustrated in figure 6. Plates were welded at flat position (PA) according to the standard EN ISO 6947. The parts were tack welded at both ends prior welding.

4.2. Wobble parameters
Also, some of the main wobble parameters were kept constant, like amplitude 1 mm and frequency 200 Hz, but oscillation mode was varied. Three different modes of oscillation was used in these tests; line oscillation, infinity oscillation and circle oscillation. 1 mm amplitude designate in wobble controller the full width movement in linear mode and diameter in circle mode. In infinity mode the length of the infinity ∞ -symbol was 0.60 mm and width were 0.24 mm. Also ordinary basic laser weld without any oscillation was made with wobble head as a reference weld.

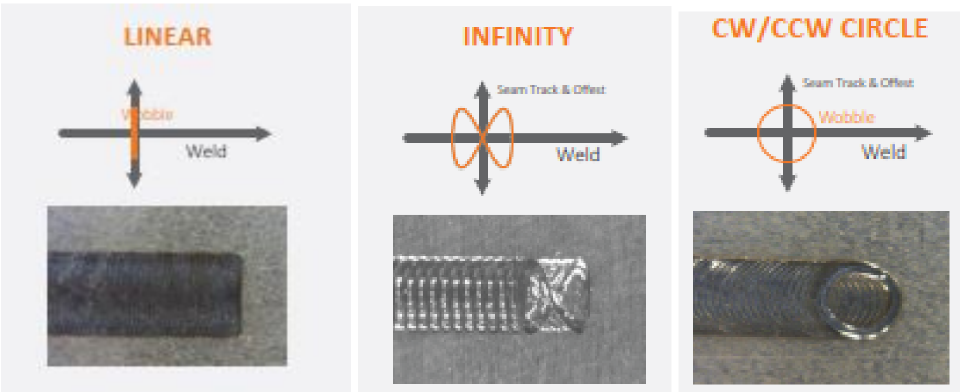


Fig. 6. Wobble head oscillation modes.

These tested wobbling parameters (dimensions and frequency) lead on roughly to the following actual focus spot speeds during the oscillation movements and welding movement; linear mode 435 mm/s, infinity mode 360 mm/s and circle mode 664 mm/s.

5. Test results
Macrographic examination and hardness tests were carried out for test pieces (Fig. 7). Specimens for macrographs and hardness testing were first cut out from welded test plates, then the edges were machined, grinded, polished and etched with 3% nitric acid, so called Nital etchant in room temperature.

Fig. 7. Laser welded test plates

5.1. Macrographs and hardness tests

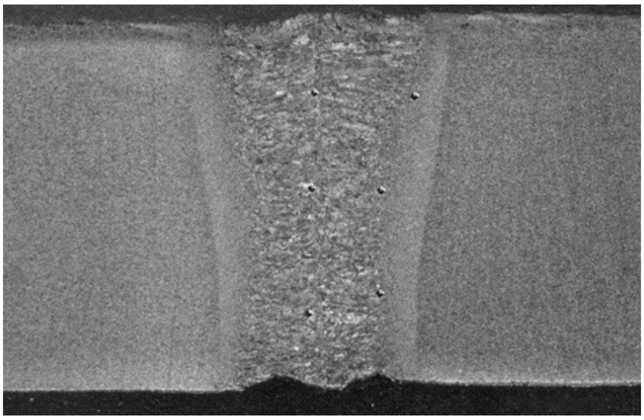
Hardness tests were made with Innovatest Falcon 600 hardness tester with 1kg force (HV1). EN ISO 22826 [5] standard was used only as a guideline for the hardness tests.

Hardness indentations are from the middle of the plate thickness (t/2), about 2 mm from surface and root, and about 1 mm from surface and root. Except all three base material (BM) hardness indentations are measured from the middle of the plate thickness several millimetres from weld (not seen in macrographs).Weld metal (WM) three hardness indentations are measured in the vertical middle line of the weld and heat affected zone (HAZ) indentations as close as possible from the fusion line. WM and HAZ indentations are shown in the macrograph figures 9, 10, 11 and 12. Measured hardness values are shown in the tables 3, 4, 5 ad 6.

Fig. 8. Innovatest Falcon 600 hardness tester

EN ISO 13919-1 [6] standard was used to evaluate weld imperfections from welds and from their cross-section macrographs. Also weld width from fusion lines was measured from macrographs from three different locations; near surface, middle and near root. Weld width values are shown beside macrograph respectively.

5.1.1. Test results from non-wobbled weld.



Weld width
2.15mm

1.40mm

1.51mm

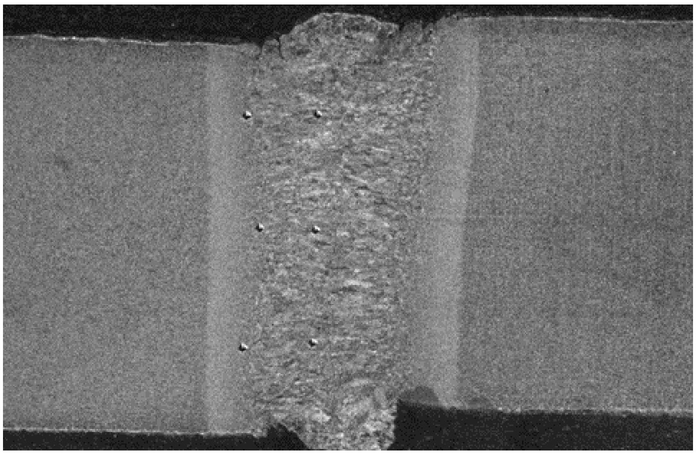
Fig 9. No oscillation (ordinary laser weld)

Imperfections; root concavity 0.19mm (level B. ≤ 0.1 t = 0.4mm)

Tab. 3. HV1 hardness from non-wobbled weld.

	BM	HAZ	WM
middle	169.46 166.81 166.87	215.4	249.66
surface		205.36	252.33
root		219.33	258.56
average	168	213	254

5.1.2. Test results from linear wobbled weld.



Weld width
1.80mm

1.50mm

1.47mm

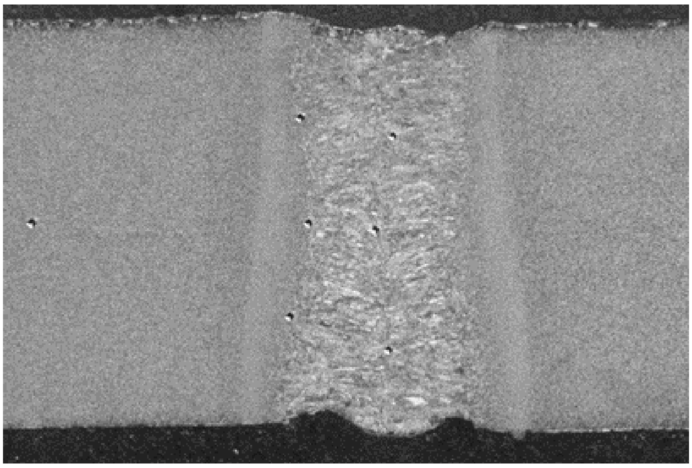
Fig. 10. Linear oscillation

Imperfections; cracks on weld surface (not permitted), linear misalignment 0.3mm (level B, ≤ 0.1 t = 0.4mm), excessive penetration 0.43mm (level B, ≤ 0.2mm + 0.15 t = 0.8mm), incorrect weld toe (<90° EN ISO 5817) [7]

Tab. 4. HV1 hardness from linear wobbled weld.

	BM	HAZ	WM
middle	186.03 185.58 185.55	222.79	255.46
surface		206.26	224.33
root		207.40	223.24
average	186	212	234

5.1.3. Test results from infinity wobbled weld.



Weld width
1.74mm

1.47mm

1.99mm

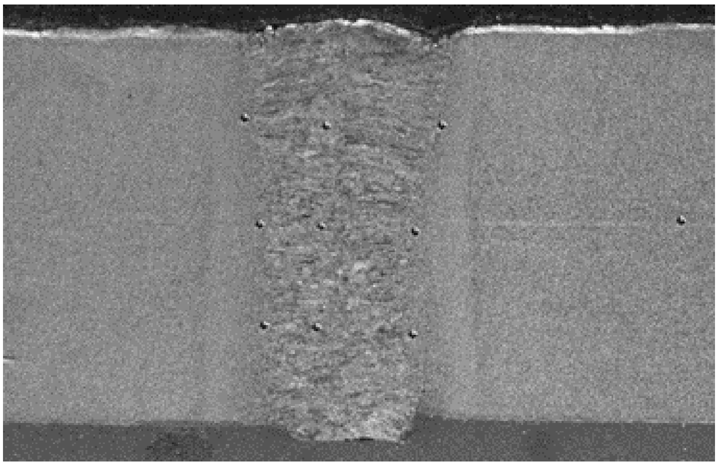
Fig 11. Infinity oscillation

Imperfections; root concavity 0.18mm (level B, ≤ 0.1 t = 0.4mm)

Tab. 5. HV1 hardness from infinity wobbled weld.

	BM	HAZ	WM
middle	184.14 179.67 173.6	230.19	253.93
surface		233.63	266.67
root		223.33	252.93
average	179	229	258

5.1.4. Test results from circle wobbled weld.



Weld width
1.91mm

1.40mm

1.46mm

Fig 12. Circle oscillation

Imperfections; crack on weld root (not permitted), excessive penetration 0.25mm (level B, ≤ 0.2mm + 0.15 t = 0.8mm), incompletely filled groove 0.17mm (level B, ≤ 0.1 t = 0.4mm).

Tab. 6. HV1 hardness from circle wobbled weld.

	BM	HAZ1	HAZ2	WM
middle	175.59 179.22 166.27	209.76	210.08	246.08
surface		197.73	202.93	256.02
root		204.3	211.44	248.76
average	174	204	208	250

6. Conclusions

In this study tested wobble features did not affect to the laser weld hardness or weld width. Average weld metal (WM) hardness value of all tests was 249HV1 (-15HV1 to +9HV1) and heat affected zone (HAZ) average value was 213HV1 (-9HV1 to +16HV1). So significant softening or any change of welded material hardness was not discovered. Probably the reason for this is, that base material (S355MC) has a low carbon content and a low carbon equivalent, which makes it less hardenable even with low heat input laser welding. Used laser welding energy input was 0.163kJ/mm.

Weld width values does not show remarkable difference between any wobble mode or even compared to the non-wobbled weld. Reason for this could be that very high focal spot motion speeds, mentioned in chapter 4.2, during oscillation does not give neither enough heat energy nor interaction time to the weld sidewalls further. This makes possible to keep keyhole and melt pool open in the middle of the weld, but not at the sidewalls, because total energy input is always the same in these tests.

Unfortunately some of the imperfections, like linear misalignment especially in linear wobbled weld (Fig. 10), were caused by the imprecise test weld set up. This unintended misalignment was bigger than in other test welds, but size of even this misalignment could actually be a typical case also in production welding. It can been seen from figure 10, that at least these tested linear wobble parameters did not give smooth root side as a result.

Also crack formation in some welds was surprise. It was thought that wobble motion shuffles weld melt pool, and slow down rapid cooling of the laser weld.

Tested wobble parameters did not cause sagging of the weld joint. Mainly because the air gap between the test plates was zero.

At the end it has to be said, that lot of further studies and experiments are needed to achieve all the advantages to the production laser welding what the beam manipulation can offer.

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[6] EN ISO 13919-1 Electron and laser-beam welded joints — Requirements and recommendations on quality levels for imperfections — Part 1: Steel, nickel, titanium and their alloys
[7] EN ISO 5817 Welding — Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) — Quality levels for imperfections