Sebastian Stano, Marek Banasik, Michał Urbańczyk

# Impact of the position of a laser beam – wire system in relation to a material being welded and of the filler metal feeding rate on the stability of laser welding with a filler metal

## Introduction

Laser radiation is one of the heat sources used in welding engineering for carrying out various welding processes. If compared with commonly applied arc heat sources, laser radiation is characterised by significantly higher power density (over $10^6$ W/cm²) which can be emitted on a material being processed. Such density enables very fast heating of metal, its melting or even evaporation and offers very precise melting of a specified volume of a material, without excessive heating of adjacent areas. By means of optical systems a laser beam can be directed at the area of processing in a very precise manner. Elements to be welded can be joined within a wide range of thicknesses [1-12].

In the recent decade or so, laser welding technologies have become increasingly popular in the welding industry as processes ensuring high quality and production efficiency. More and more often welding production utilises the process of laser welding which, in many cases, makes it possible to significantly simplify a structure to be welded and reduce production time if compared with the production of structures made by means of classical welding methods. Laser welding is usually conducted without a filler metal, and a weld is formed by a metal coming from the molten edges of materials being joined. Such an approach to the process of welding entails meeting high requirements related to the accuracy of the preparation and positioning of the edges of elements to be welded (there should be no gap between such elements) and limits the use of the process in situations requiring the feeding of a filler metal ,e.g. the modification of the chemical composition of a weld, welding butt joints positioned with a gap or making typical fillet welds [1-5].

This article presents a fragment of research conducted at Instytut Spawalnictwa, concerning laser welding with a filler metal wire and focused on the stability of filler metal-utilising laser welding of butt joints positioned without a gap [1].
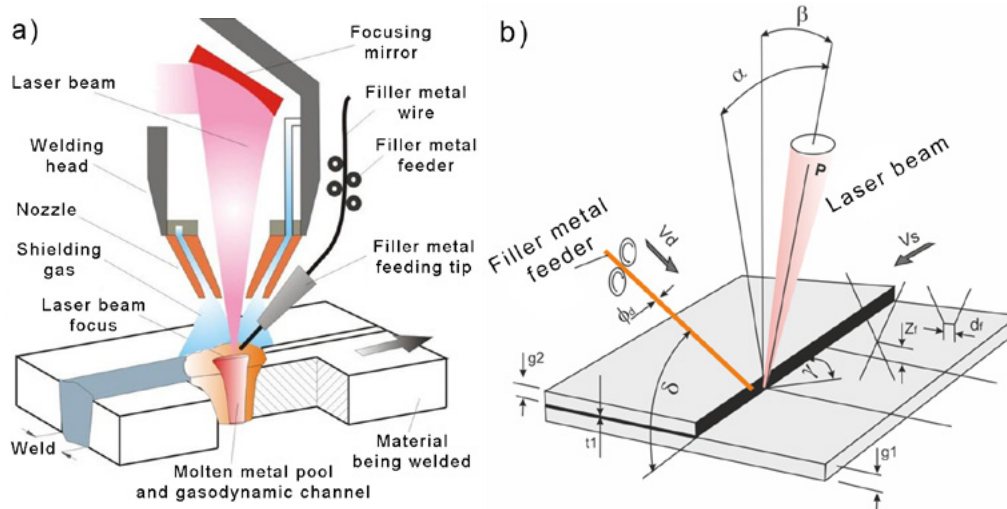


Fig. 1. Scheme of laser welding with a filler metal wire:
a – scheme of a butt joint welding process;
b – marked geometrical dependences of the system: laser beam – filler metal wire –
material being welded in the scheme of overlap joint welding process

Sebastian Stano PhD Eng., Marek Banasik PhD Eng., Michał Urbańczyk MSc Eng. – Instytut Spawalnictwa, Zakład Technologii Spawalniczych /Welding Technologies Department/

## Laser welding with filler metal wire

Laser welding with a filler metal in the form of a wire is technically significantly more complicated than melting not bevelled edges with a single run of a laser beam. It is necessary to ensure the stability of a welding process "disturbed" by introducing a filler metal. The required stability can be guaranteed by a precise selection of a number of parameters such as the power of a laser beam, welding rate and a filler metal feeding rate. Very important is the proper positioning of the wire end and the laser beam in space (Fig. 1). In addition to parameters related to the amount of heat supplied to the joint area, the appropriate positioning is of crucial importance for the stability of laser welding with a filler metal wire.

The process of laser welding with a filler metal considerably differs from arc welding processes with a filler metal such as MIG, MAG or MMA. During arc welding drops of molten electrode metal (electrode wire) are carried to a weld (to a liquid metal pool) by a gravitational force and forces present in an electric arc. In case of modern welding equipment, the modification of the current parameters of an arc welding process, e.g. MIG/MAG makes it possible to precisely control, using advanced control systems, the manner of metal transfer depending on a metal arc type (e.g. short-circuit arc, spray arc). In turn, during laser welding the filler metal is transferred to the area formed during the welding process (gasodynamic channel and molten metal pool) as a result of the impact of gravitational force as well as forces connected with liquid metal viscosity and surface tension present on the phase boundary on the liquid metal.

## Test equipment and materials

Tests of laser welding with a filler metal wire were carried out using a solid-state laser, integrated with a robotised system for laser processing, installed at Instytut Spawal-
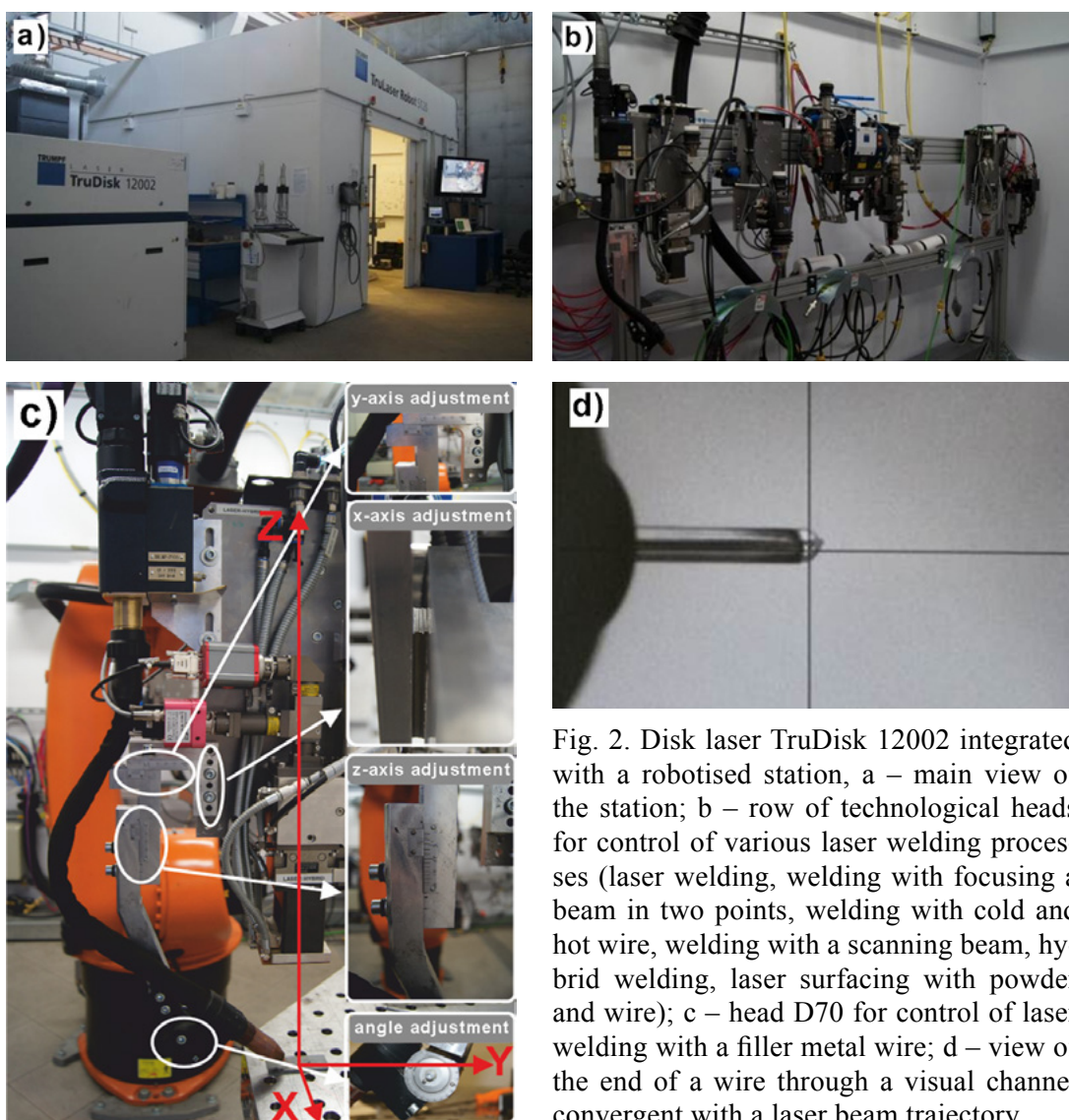


Fig. 2. Disk laser TruDisk 12002 integrated with a robotised station, a – main view of the station; b – row of technological heads for control of various laser welding processes (laser welding, welding with focusing a beam in two points, welding with cold and hot wire, welding with a scanning beam, hybrid welding, laser surfacing with powder and wire); c – head D70 for control of laser welding with a filler metal wire; d – view of the end of a wire through a visual channel convergent with a laser beam trajectory

nictwa. This laboratory station fully meets the requirements for modern industrial stations and is equipped with the following:

• Laser TruDisk 12002 – a solid-state laser type Yb:YAG manufactured by the Trumpf company; the maximum power: 12 kW; the quality of a laser beam specified by parameter BPP ≤ 8 mm×mrad Laser TruDisk 12002 (Fig. 2) is equipped with a system for controlling 4 visual outputs, making it possible to lead four independent optical fibres through four independent visual routes out of a resonator and the programme-aided selection of a fibre optic through which a laser beam will be emitted. The laser is connected with fibre optics via an LLK D interface (the Trumpf company standard) with diameters of 200μm, 300μm, 400μm and 600μm. Each of the fi-

The mechanism of a joint formation during laser welding with a filler metal wire was observed and recorded and using the following:

• digital camera manufactured by Sony, operating in a time-lapse photography mode with a system of diaphragms enabling the recording of very bright areas of the laser beam operation.

• fast camera V5.1 manufactured by Vision Research Phantom, recording a colour image at a rate of 1,200 exposures/s with a maximum resolution of 1024×1024 pixels. The maximum rate of recording depends on the resolution of an image to be recorded (max. approximately 100 000 exposures/s). The resolution of images used in the tests was 768×384 pixels; the rate of recording was 2 000 – 2 400 exposures/s.

Table 1. Chemical composition of parent and filler metals used in tests

| Grade | C [%] | Fe [%] | Al [%] | Si [%] | Mn [%] | Cr [%] | Cu [%] | P [%] | S [%] | Ni [%] |
|---|---|---|---|---|---|---|---|---|---|---|
| S355J2 | 0,19 | rest | 0,034 | 0,19 | 1,34 | 0,02 | 0,05 | 0,015 | 0,009 | 0,02 |
| G4Si1 PN-EN 440 | 0,08 | - | max. 0,95 | | 1,70 | - | - | max. 0,025 | max. 0,025 | - |

bre optics can be connected to a working head suitable for a given type of laser processing. In accordance with the dependence $d_{og} = d_{św} \times f_{og}/f_{kol}$, the diameter of a beam focus depends, in direct proportion, on the diameter of the fibre optic and the focal length of the focusing lens, and in inverse proportion to the focal length of a collimator lens. Hence, changing the diameter of a fibre optic only, one can adjust the diameter of the laser beam focus spot;

• A row of technological heads (Fig. 2b), including heads enabling the control of laser welding with a filler metal (Fig. 2c) in the form of a wire, fixed to the coupling of an industrial robot KR30HA manufactured by the Kuka company, confined in a working booth.

• A monitoring system PD2000 produced by the Prometec company. The system consists of an industrial computer with appropriate software for image analysis, an expansion card for capturing images and a special camera CMOS introduced to the optical system of the laser beam. The camera was connected to the visual route of the head D70 and recorded the image of a welding process for various settings of welding parameters. Images were uploaded to a computer at a frequency of approximately 1 kHz, depending on the size of an image used for data analysis. The obtained sequence of images enabled the observation and analysis of changes taking place in the weld eye during welding.
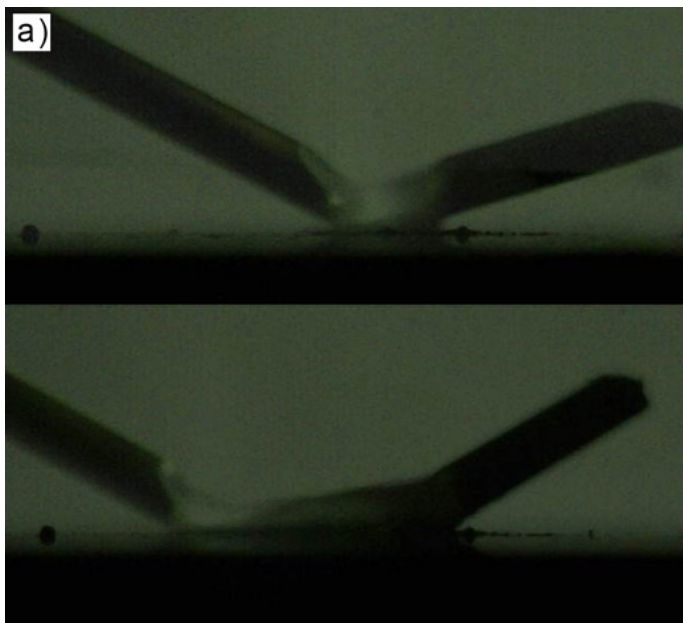
Fig. 3. Commencement of laser melting with a filler metal with excessive exposed length of the wire recorded with a fast camera (a); the view of the face of a fusion bead with a wire end welded onto the beginning of the bead (b)

The technological welding tests involved the use of a heightened strength steel plate (grade S355J2) (Table 1). The applied filler metal was a standard electrode wire used for MIG/MAG welding, with a diameter of 1.2 mm (Table 1). The shielding gas was argon 4.6 blown through a system of four dragged nozzles, each with an outer diameter of 8 mm; the shielding gas flow rate was 24 l/min.

## Course and results of tests

The tests of the stability of laser welding with a filler metal wire were carried out recording the process of laser melting of a 5mm-thick steel plate, imitating the conditions for welding butt joints with the square preparation of plates, without a gap between materials to be joined. On the basis of initial tests, the welding linear energy (laser beam power and welding rate) was adjusted in a manner which enabled obtaining the fusion of approximately ⅔ of the plate thickness during laser melting without feeding a filler metal (Table. 2).

The above process parameters made it possible to capture the fusion shape changes, depending on modified process parameters, which would have been impossible or highly hindered in the case of full fusion.

The process of laser melting without a filler metal, with melting parameters as presented in Table 2, was stable. The obtained penetration depth amounted to 3 mm. The shape of the fusion bead face was regular, with a slight (0.3 mm in height) reinforcement.

During the initial tests of laser welding with a filler metal, it was possible to observe that changing the angle of wire inclination $\delta$

Table 2. Basic output parameters of laser welding with a filler metal wire

| P [kW] | Vs [m/min] | Vd [m/min] | f [mm] | $d_{og}$ [mm] | z [mm] | $\delta$ [°] | $\varnothing_{dr}$ [mm] | Q [l/min] |
|---|---|---|---|---|---|---|---|---|
| 3,2 | 2 | 0 | 0 | 0,6 | 0 | 45 | 1,2 | 24 |

| | |
|---|---|
| P – | power of a laser beam at the spot in which a laser beam affects the material; |
| Vs – | welding rate; |
| Vd – | filler metal (wire) feeding rate; |
| f – | location of a laser beam focus in relation to the wire; |
| z – | location of the system: wire – laser beam in relation to the surface of welded material; |
| $\delta$ – | inclination angle of wire in relation to the surface of material being welded; |
| $\varnothing_{dr}$ – | wire diameter (i.e. filler metal wire diameter); |
| Q – | shielding gas (argon) flow rate. |

in relation to the surface of the plate subjected to melting within a 30°-60° range had no significant effect on the course of the process. Changing the wire inclination angle outside the range mentioned above proved impossible due to the design of the wire feeding system. A wire inclination angle greater than 60° prevented the wire from being fed directly into the laser beam focus area without disturbing the laser beam trajectory (covering the laser beam trajectory by the elements of the wire feeder holder, which might result in an uncontrolled reflection of the laser beam or could damage the holder). A wire inclination angle below 30° could result in a collision of the holder with the material being welded.

The end of the wire was pointed directly to the laser beam focus (Fig. 2d) located on the surface of the material being melted. Such positioning required stiffening the wire feeder holder so that it would not change it position during the tests. With the holder positioned as described above it is important to ensure a previously specified constant exposed length of wire amounting to 9-11 mm. An exposed length of wire that was too short prevented the wire from being melted at the initial area of the bead, and the laser beam directly affected the material to be melted. In turn, an exposed length of wire that was too long caused the extended wire end to be pressed against the plate surface, and as a result, at the initial stage, the laser beam melted the wire through, dividing it into two parts (Fig. 3a). In consequence, the spot at which the process started was covered with a wire end welded onto the surface and difficult to remove (Fig. 3b). In an extreme case, the welded-on wire end could cause a collision with the shielding gas nozzle, disturbing or even eliminating the gas shielding. In the case of the complete integration of the shielding gas nozzle with the technological head, such a collision could pull elements being welded out of the fixing device or even damage the head. The setting of the exposed length of the wire should be automatic. After the completion of a welding process, well selected process parameters result in setting the exposed length of the wire at a desired level. In order to ensure a
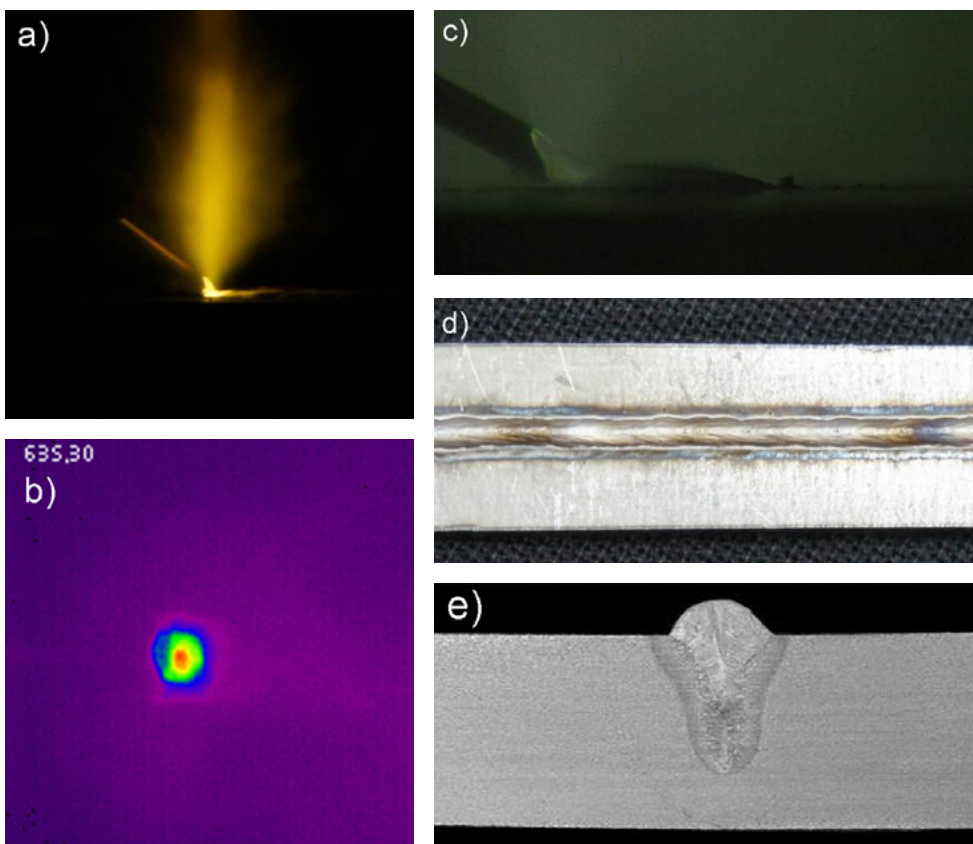


Fig. 4 Photograph of stable laser melting with a filler metal wire:
a, c – liquid metal formed at the end of the wire fed to the welding area;
b – stable gasodynamic channel recorded by the system PD2000;
d – example of the fusion face made with the filler metal wire;
e – macrostructure of obtained fusion.

permanently exposed length of the wire, independent of possible disturbance, the wire can be automatically cut by the laser beam before starting each bead. It is also possible, as in robotised MIG/MAG welding, to employ an automated and mechanised shear.

After starting the process of laser melting with a filler metal, the wire permanently fed to the area of the laser beam operation is partly melted by the laser beam and partly by the heat emitted in the area of the laser beam effect on the material being welded. The heat absorbed by the wire end causes the wire end itself to become heated to a
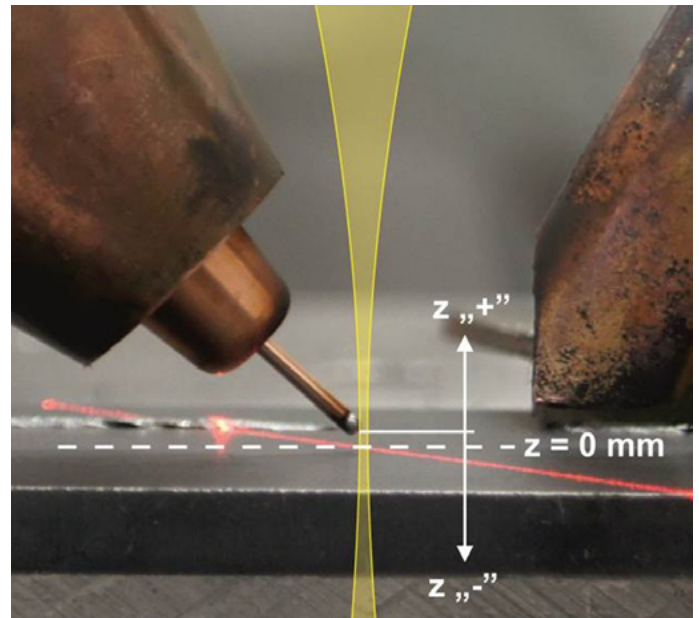


Fig. 5. Visualisation of changing the location of the laser beam-wire system in relation to the plate surface

temperature exceeding the melting point of the wire. When the process is stable, on the face surface of the wire a thin layer of a molten metal and a liquid bridge between the wire and the welded material are formed (Fig. 4a,c). The wire is fed permanently, the size of the liquid bridge and the amount of metal flowing to the formed weld pool becomes stable and strictly depends on the linear energy of welding and on the wire feeding rate. A newly formed gasodynamic channel, characteristic of laser welding processes with high power density, remains stable and undisturbed by the metal flowing from the molten wire (Fig. 4b). For properly selected welding process parameters, the weld face was characterised by a constant width and a regular shape. On the surface of the weld face one could observe small and regular flakes connected with the gradual solidification of the liquid metal of the weld pool formed around the capillary (Fig. 4d).
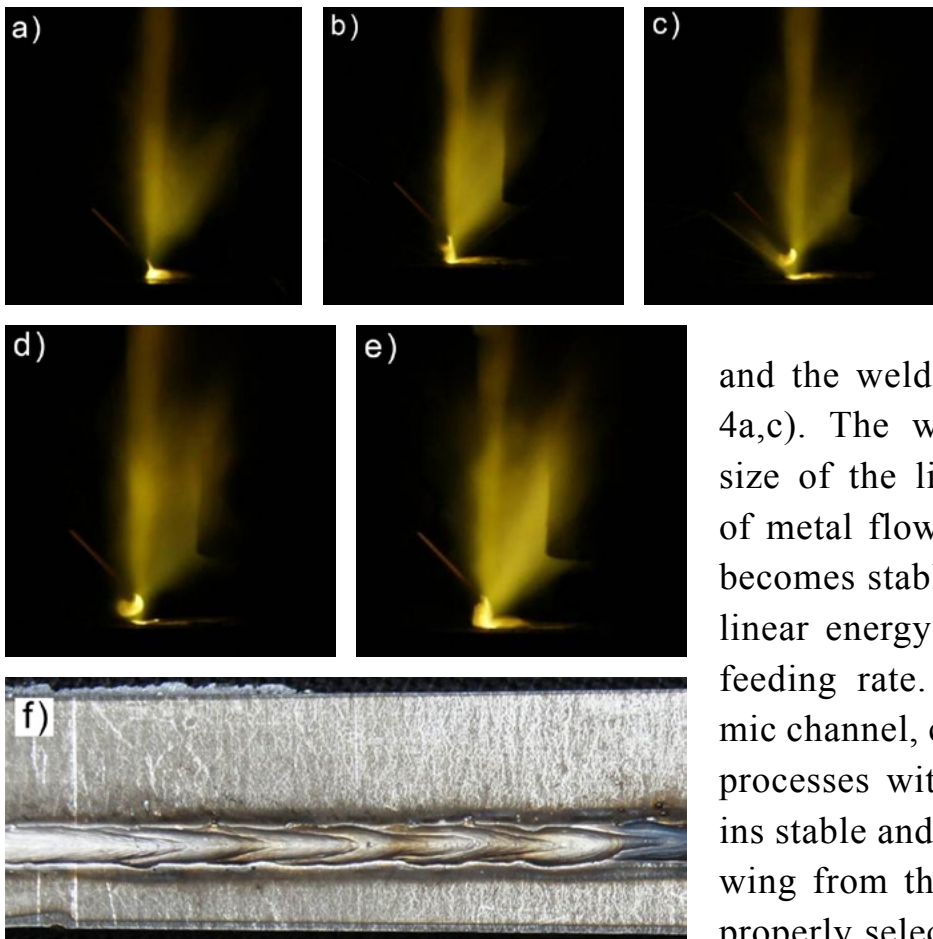


Fig. 6. Sequence of photographs capturing the process of laser melting with the filler metal wire and the view of the bead face taken for moving the location of the laser beam-wire system in relation to the molten plate by 1 mm:
a – stable welding process ;
b – elongation of the liquid metal bridge;
c-d – formation of the liquid metal drop at the end of the wire;
e – contact of the drop with the weld pool and the flow of the liquid metal from the wire to the pool.

The tests revealed that the stability of laser melting with a filler metal wire is strongly affected by the position of the laser beam–wire system in relation to the surface of the material being welded (Fig. 5). Already for the quantity z = 1 mm (Table 2) the liquid metal bridge elongates, often losing its continuity (Fig. 6b). The emergence of a discontinuity is accompanied by the formation of a liquid metal drop at the end of the wire. Afterwards the drop grows until touching the material being welded (Fig. 7c-d, 8b-d). The molten metal flows into the pool and, by solidifying, forms the fusion area (Fig. 7e, 8e-f). Due to a relatively small distance to the material being melted, the liquid metal drop formed at the end of the wire quickly touches
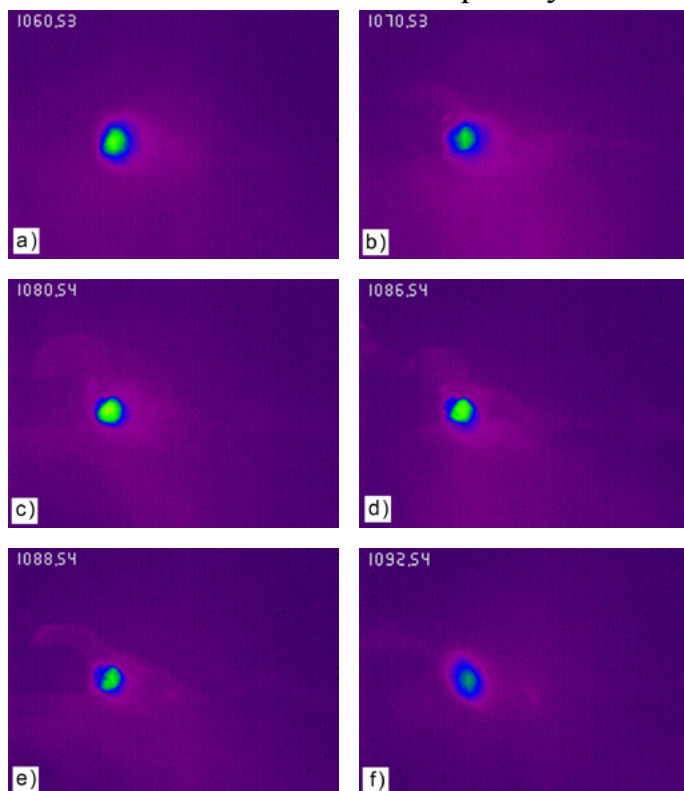


Fig. 7. Exemplary sequence of photographs capturing the process of laser melting with the filler metal wire recorded by the monitoring system PD2000. Change of the location of the laser beam-wire system in relation to the molten plate by z = 1 mm:
a – proper course of the welding process;
b – d – growth of the liquid metal drop
at the end of the wire;
e - f – contact of the drop with the weld pool
and the flow of the liquid metal to the pool;
disturbed gasodynamic channel.

the liquid pool thus ensuring the permanent inflow of the filler metal. On the face of the fusion bead one can observe characteristic, regularly arranged flakes, indicating spots at which the drop formed at the end of the wire touched the liquid metal (Fig. 7f).

Further increasing the distance between the laser beam-wire system and the surface of the plate being melted destabilises the process. As a result, a liquid metal drop is formed at the end of the wire. Affected by gravitation, the drop enters the parent metal (Fig. 8). On the face of the fusion bead one can observe the formation of humps at the spots of the contact between the liquid metal drop and the base. The humps are responsible for the variable geometry of the fusion bead (Fig. 8h-i). The bottom part of the bead may contain imperfections (voids) formed as metal vapours present in the capillary are confined by the capillary-filling liquid metal of the drop passing from the wire to the weld pool.

Shifting the laser beam-wire system inside the material being melted does not significantly deteriorate the stability of the welding process as in the case of lifting the aforesaid system. The wire is pressed against the surface of the molten plate by the shifted tip of the wire feeder. The wire bends elastically, changing the angle of entering the laser beam operation area. If the exposed length of the wire is not set at the level required before the commencement of the welding process, a non-melted wire end may appear at the beginning of the bead, similarly as in the case of laser welding with the a filler metal wire with the proper positioning of the geometric system: laser beam-wire-melted material, but with an excessive length of the wire. Test results not presented in this article reveal that during welding butt joints positioned with a
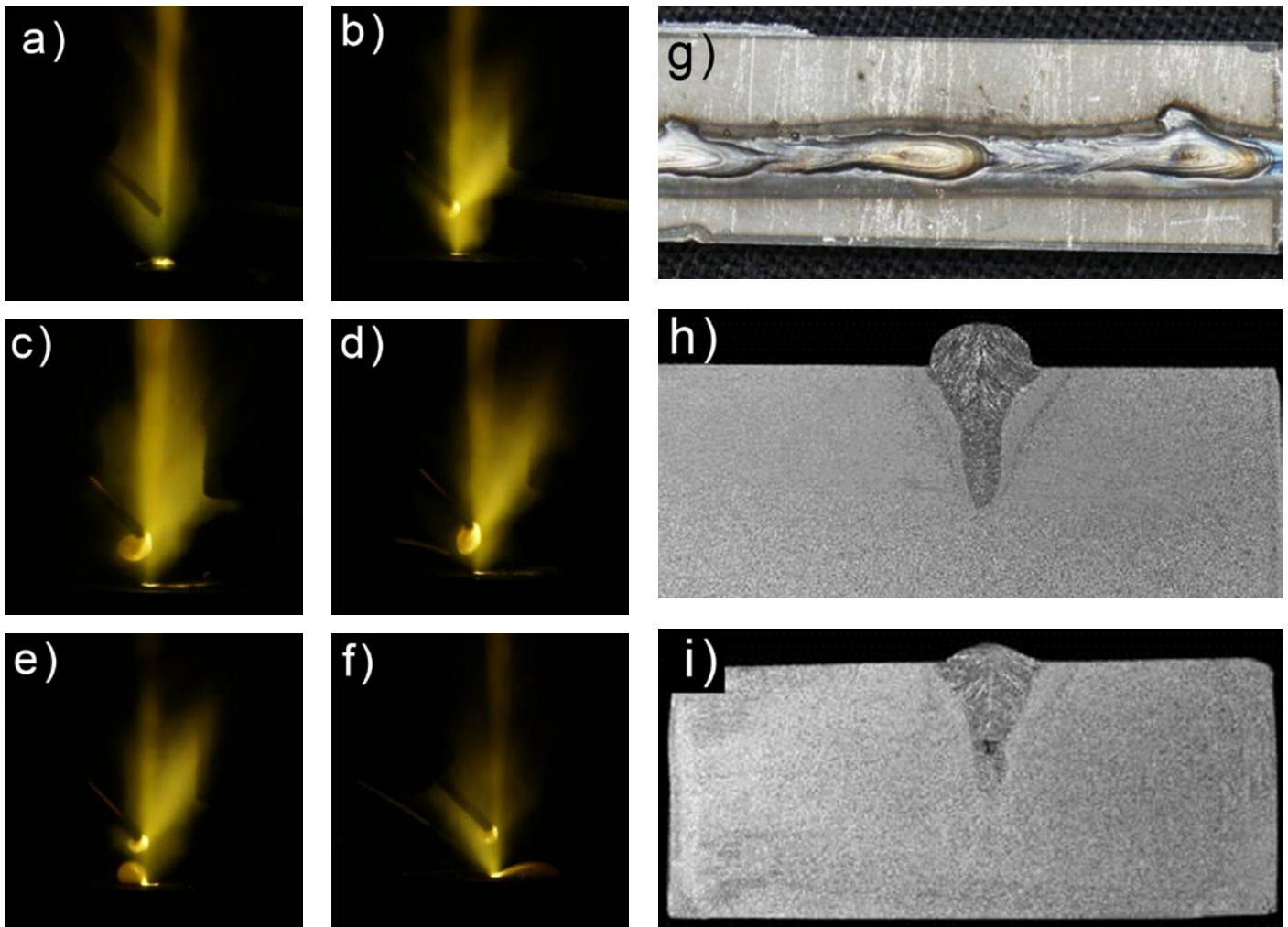
Fig. 8. Exemplary sequence of photographs capturing the process of laser melting with the filler metal wire as well as the view of the face and the macrostructure of the fusion bead made for the shift of the location of the laser beam--wire system in relation to the molten plate surface by 4 mm

a – start of the process; b-d – formation of the liquid metal drop at the end of the wire; e-f – thick-drop flow of the liquid metal from the wire to the weld pool; g – characteristic humps at the end of the bead; h – bead macrostructure at the hump; i – bead macrostructure outside the hump.

gap, the stability of the process when the laser beam-wire system is shifted below the surface of joined plates also depends on the size of a gap.

Changing the position of the laser beam--wire system in relation to the surface of the plate does not change the mutual position of the beam and the wire (the wire is always introduced to the laser beam focus) but results in a change of the location of the laser beam in relation to the surface of the plate being melted. The measurements of the geometrical quantities of the fusion bead revealed that the greatest penetration depth was obtained for the "0" position of the system, i.e. for the greatest density of power emitted in the laser beam operation area (Fig. 9). The optical system of the working head used in the tests, owing to the high quality of a generated laser ray, was characterised by the depth of laser beam focus (Rayleigh length) of 5.625 mm. Therefore, changing the position of the beam focus in relation to the plate by 4 mm resulted in a relatively small change of the penetration depth – below 0.4 mm. Due to the loss of process stability while lifting the laser beam-wire system in relation to the surface of the material being welded, the estimated geometrical dimensions for positive shifts – above 2 mm – are not reliable.
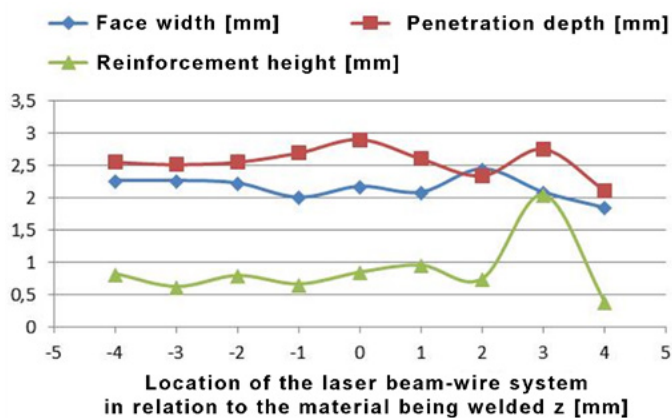
Fig. 9. Impact of the change of the location of the laser beam-wire system in relation to the plate being melted on the penetration depth, face width and reinforcement height in the process of laser welding with the filler metal wire ($V_d = 1.5$ m/min, other process parameters as in Table 2)

The analysis of time-lapse photographs and images obtained from the system PD2000 revealed that for the whole constant linear energy of laser melting with a filler metal wire (welding power and rate) it is possible to determine the minimum and maximum filler metal feeding rate at which the welding process is stable. As a rule, the knowledge of the minimum filler wire feeding rate at which the welding process is stable is not necessary in industrial conditions. If a welding engineer technologist decides to use the process of laser welding with a filler wire, they usually search for such a filler wire feeding rate which will meet their requirements and for which the welding process with a filler metal wire was used to produce a given structure (making a fillet weld of a specified height, specified chemical composition of a weld, filling the gap in a joint etc.).

If the filler metal feeding rate is too low the amount of heat coming from the laser beam effect on the wire and the material being welded may be able to melt a bigger section of the wire end. Such a situation may result in breaking a liquid metal bridge formed during the process, the formation of a drop at the end of the wire and momentary disturbance of the process stability. However, the disturbance is not visible on the face of the weld due to the relatively small amount of the filler metal transported to the weld pool and a short-duration character of the disturbance. Such momentary changes are difficult to capture also for the monitoring system PD2000 as they do not generate significant changes in the brightness intensity of individual spots of an area under observation. The characteristic of a welding process with a filler metal feeding rate that is too low is the frequent formation of a metal drop at the end of the wire towards the end of the process (deactivation of the laser beam and stopping the filler metal feeding process). The drop fails to pass to the weld pool due to the breaking of the liquid metal bridge shortly before the end of the process. If there is no programme sequence cutting the wire, its end formed as described above may disturb the process at the place where the welding of the next bead is to be initiated.

A filler metal feeding rate that is too high causes the energy supplied to the welding area to be insufficient for stable and permanent wire melting. After a momentary welding process stability (Fig. 10a), the wire enters the laser beam operation area more deeply, covering a formed gasodynamic channel. The volume of liquid metal at the end of the wire and in the liquid metal bridge increases (Fig. 10b-c). A relatively large volume of the liquid metal flows to the weld pool, flooding the gasodynamic channel. Additionally, non-melted wire enters the back area of the pool, pushing out the liquid metal, which, by solidifying, forms characteristic humps of the weld face (Fig. 10 d-f). The lack of the gasodynamic channel stability causes the penetration depth, as well as the

width and height of the weld face, to change along the length of the weld and the fusion process is not repeatable. At the hump areas, the reinforcement of the face is characterised by great asymmetry. For the melting parameters used in the tests (Table 2), the boundary filler metal feeding rate, at which the first symptoms of the process instability could be observed, was the rate of 2.5 m/min. At a fil-
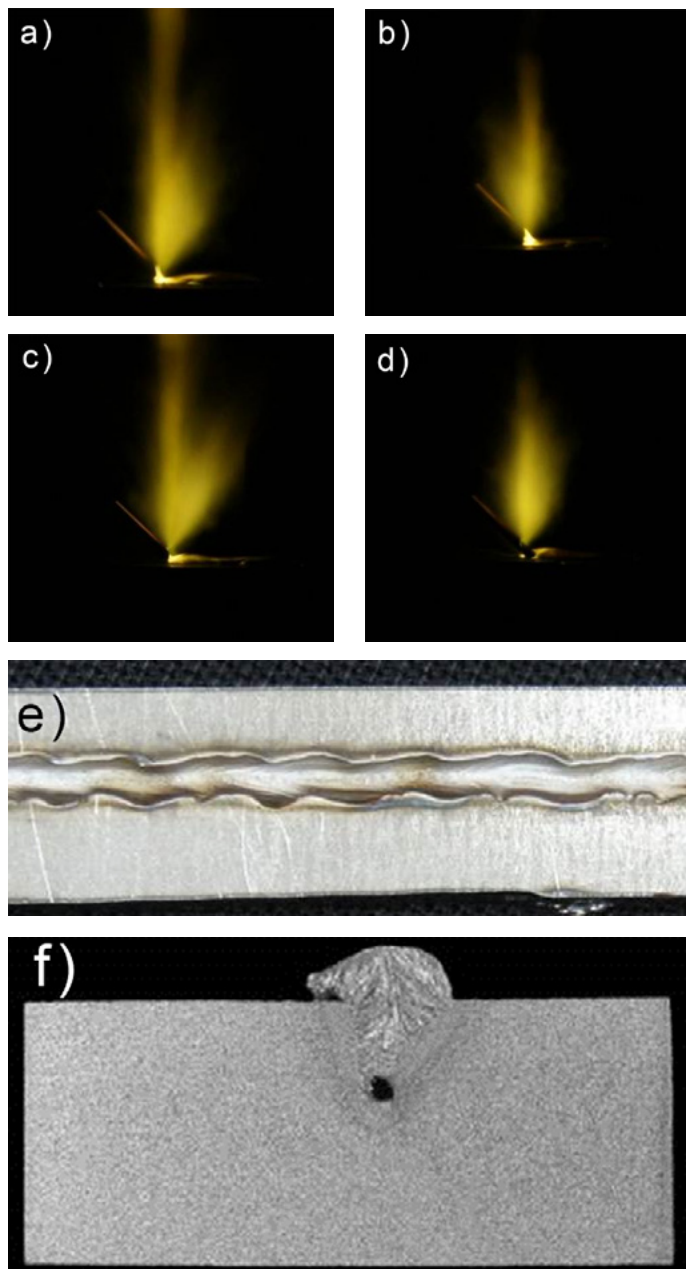


Fig. 10. Exemplary sequence of photographs presenting the process of laser melting with the filler metal wire at a filler metal feeding rate of 3 m/min:
a – proper course of the melting process;
b – increased volume of the liquid metal bridge;
c, d – wire partly (c) and entirely (d) covering the laser beam and the capillary;
e – view of the bead face;
f – macrostructure of the bead at the hump

ler metal feeding rate of 3 m/min, the changes in the course of the process, changes of the face width and humps were very visible and easy to capture (Fig. 10e).

The geometrical measurements of fusion shapes obtained in the tests (Fig. 11) revealed that for lower filler metal feeding rates and process parameters used in the tests (Table 2), no significant changes of the penetration depth were obtained. The greatest penetration depth of 3 mm was obtained for laser welding without a filler metal (Vd = 0). For a filler metal feeding rate of up to approximately 1.5 m/min the differences of the penetration depth amounted to 0.1 mm i.e. within the measurement tolerance.
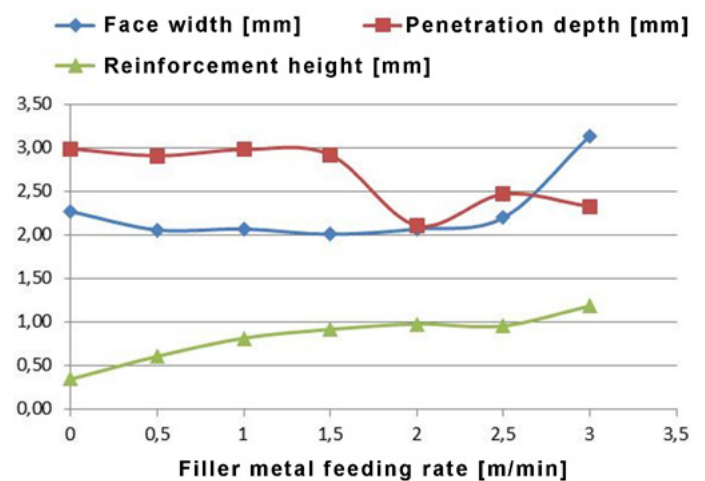


Fig. 11. Impact of the filler metal feeding rate on the penetration depth, face width and reinforcement height during laser melting with a filler metal wire (process parameters from Table 2)

A filler metal feeding rate of 2 m/min caused a sharp decrease in the fusion depth. This phenomenon can be attributed to a fusion-formation mechanism observed during the process, where a filler metal feeding rate of 2 m/min ensured the stability of the process, but the wire covered a slight part of the laser beam, more of which (than in the case of a lower filler metal feeding rate) was used directly for melting the wire. The results of the measurements for a filler metal feeding rate of 3 m/min should not be taken into con-

sideration due to the process instability and changeability of measurement results depending on a spot at which the measurements were carried out.

The filler metal wire fed to the melting area is used for making the reinforcement of the fusion bead, the height of which almost in direct proportion increases along with an increase of the filler metal feeding rate. The width of the bead face changes within a small range and only after the appearance of instability intensively increases at the spots of the humps of the fusion bead face.

## Summary

The conducted tests revealed that the stability of laser melting with a filler metal wire depends on the mutual geometrical positioning of the system: the laser beam, the wire end and the material being welded. A stable process of melting was obtained when the laser beam affected directly the end of the wire fed to the melting area and the end of the wire was placed directly on the surface of the plate being melted. The wire can also be pressed against the surface of the plate being melted by the force of the elastic bending of the wire caused by the 2mm-long shift of the wire-laser beam system towards the plate surface. Such a positioning enables the formation of a liquid bridge at the end of the wire and the stable flow of the liquid metal into the weld pool. Properly selected heat input parameters of the process (the power of a laser beam, welding rate and the location of the laser beam focus) as well as the amount of the filler metal fed to the melting area make it possible to create a gasodynamic channel and obtain penetration depth values comparable with those obtained in the process of laser welding without a filler metal. The molten filler metal from the wire may cause short-duration instabilities of the gasodynamic channel which do not affect the general stability of the process and the appearance of the fusion bead face. Lifting the laser beam-wire system in relation to the plate being melted by 1 mm significantly disturbs the flow of the liquid metal from the end of the wire into the weld pool. A liquid metal drop formed repeatedly at the end of the wire detaches cyclically from the wire and forms the uniform hump of the face. For the constant linear energy of laser melting with a filler metal wire (welding rate and power) and with properly adjusted parameters of the positioning of the system: the laser – the wire – the surface of the plate being melted it is possible to determine the minimum and maximum filler metal feeding rate ensuring the stable course of the process.

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