Jerzy Dworak

Impact of laser beam shape on YAG pulsed laser welding

Introduction

Laser radiation beams are utilised in a variety of technological processes, having become nowadays an almost universal heat source. Typical applications such as cutting, welding and marking are being supplemented by such processes as surface hardening, surfacing by welding, re-melting, micro-machining and others. These technological processes can be carried out using various sources of laser radiation e.g. CO_2 lasers, YAG lasers or HPDL lasers. YAG lasers are, at present, becoming increasingly popular, resulting from the significant power of a radiation beam (more than ten kilowatts) reached by the latest generation of devices available on the market and due to the efficient absorption of radiation, particularly by strongly reflective metals, when compared to e.g. CO_2 lasers, This fact makes it possible to apply the YAG solution to an increasing number of industries, including areas which have not been available for these lasers until today.

YAG lasers of power in excess of ten kilowatts constitute one of the two groups of lasers of this type. The other is composed of low-power YAG lasers (of power up to 1kW), applied mainly in precision engineering, where their position is particularly strong due to, among others, the high quality of the radiation beam.

One of the characteristics of YAG lasers is the possibility of the emission of a radiation beam in a pulsed mode. High-power YAG lasers may be applied in such a mode, whereas low-power YAG lasers are usually applied in this mode.

In the case of many technological processes, welding in particular, considerable importance is attached to the possibility of shaping individual radiation beam pulses through defining various courses of power changes within the duration of a pulse. The combination of the repetition frequency and the possibility of shaping a pulse within a significant pulse duration enables precise control of the heat supplied to the material being processed, which is of particular importance during the welding of precision elements using a low-power radiation beam.

Power parameters of laser radiation emitted in pulsed mode

The emission of YAG laser radiation in pulsed mode results from the pulsed excitation of the laser resonator. This excitation is implemented through optical pumping (the illumination of a resonator with radiation pulses of laser diodes grouped into so-called packages i.e. modules consisting of a specific number of diodes). A characteristic feature of the operation of YAG crystalline lasers is the generation of significant amounts of heat by these pumping modules, which constitutes the limitation of the maximum value of the average power and energy of a radiation beam pulse (basic parameters of the operation of pulsed lasers). The energy of a pulse depends upon the com-

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bination of its power and width (duration). Therefore, these radiation beam parameters cannot be shaped freely, as one cannot freely define the duration and emission frequency of a pulse for the assumed value of the average power of a radiation beam. The energy of a pulse cannot exceed the maximum value defined for a given resonator.

The average power of laser radiation in pulsed mode is defined as the product of the average power of the radiation of one pulse P_i, the duration of this pulse t_i and the number of pulses per a second expressed through the frequency of emission f. For a given average power there is a number of combinations of the selection of pulse energy and pulse repetition frequency.

$$P_{śr} = P_i \times t_i \times f = E_i \times F \tag{1}$$

The frequency of a pulse emission is a parameter closely related to the period of their occurrence expressed in the following relation:

$$T = \frac{1}{f} \qquad \left[s = \frac{1}{Hz} \right] \tag{2}$$

The average energy of laser radiation for the pulsed operation mode is defined as the product of the average radiation power and radiation beam action time.

$$E_{śr} = P_{śr} \times t \qquad [J] \tag{3}$$

In the case of single pulse spot welding, an important parameter is the density of pulse power.

$$GP_i = \frac{P_i}{A} = \frac{E_i}{t_i \times A} \qquad \left[\frac{J}{s \cdot m^2} \right] \tag{4}$$

where A represents the focusing area of a radiation beam.

In the case of a pre-defined average power of a radiation beam $P_{śr}$, the density of the power supplied to the area unit, i.e. the average area power density, is determined by means of the following quotient:

$$GP_{śr} = \frac{P_{śr}}{A} \qquad \left[\frac{W}{m^2} \right] \tag{5}$$

The quotient of the area power density $GP_{śr}$ and radiation beam action time determines the average area power density:

$$GE_{śr} = GP_{śr} \times t \qquad \left[\frac{J}{m^2} \right] \tag{6}$$

The quantities defined above are presented in Figure 1.

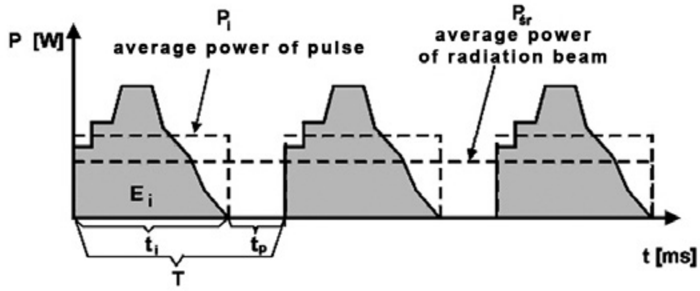


Fig. 1. Graphic interpretation of average power of pulse P_i, average power of radiation beam $P_{śr}$, pulse energy E_i, pulse duration t_i, pause time t_p pulse period T

A weld produced by a laser beam emitted in pulsed mode is composed of a number of overlapping spot welds. The degree of overlapping of individual pulses expressed in percentage, i.e. the so-called overlap, represents the degree at which the area of a material molten by a single pulse overlaps a similar area produced by the previous pulse. By means of a specific overlap one can control the amount of heat supplied to a material being welded, as well as influence the homogeneity of the structure of a weld.

The overlap is defined by the rate of the welding process appropriately selected in relation to the frequency of pulses. In turn, the frequency of pulses depends on the pre-defined power of a pulse and its duration. If an area molten by a single pulse of a laser beam takes an elliptic shape (as a result of the process being carried out at a specific rate), the longer axis of the ellipse is designated as the dimension S, whereas the shorter one as the dimension D (Fig. 2,3)

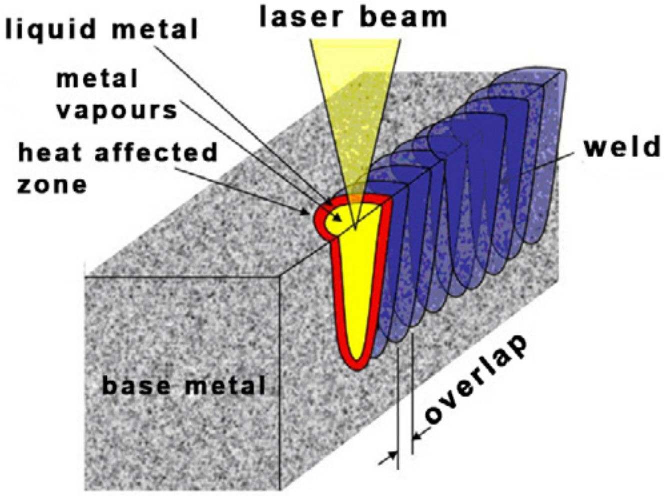


Fig. 2. Scheme of process of laser welding with radiation beam emitted in pulsed mode

Degree of overlapping of pulses is defined by the following relation:

$$Z = \frac{[S - S']}{S} \times 100\% \qquad (7)$$

where:

$$S = D + v \times t_i \qquad (8)$$

$$S' = v \times T \qquad (9)$$

After transformation of relations 7, 8, 9, the overlap Z is the following:

$$Z = \left[1 - \frac{v \times T}{D + v \times t_i}\right] \times 100\% \qquad (10)$$

Effective penetration depth is conditioned by the overlap Z (Fig. 3).

Welding with laser radiation beam emitted in pulsed mode

The miniaturisation in many areas of technique has almost become a trend, stimulating the development of micro-machining (including micro-joining) of various structural materials. In relation to miniature structural elements and modules, as well as a variety of miniature components and devices, today's manufacturing techniques and classical joining technologies in particular meet technical limitations preventing the efficient use of the former. In many applications the only solution is the laser, regarded as one of the most innovative tools of modern industry.

Operating a laser in pulsed mode enables the precise production of welded joints of elements made of technologically advanced materials and having minute dimensions. A joint of this type is obtained through the melting of a very small amount of metal by a single pulse of a laser beam and its immediate crystallisation. A continuous weld is formed as a result of the proper selection of welding rate and pulse repetition frequency.

Pulsed laser welding is applied where one needs to join ready-made electronic components in a tight housing, thin-walled elements (membranes) with massive cases, thin-walled housings, medical equipment elements (housings of cardiac pacemakers, endoscopes, medical implants, surgical instruments and others).

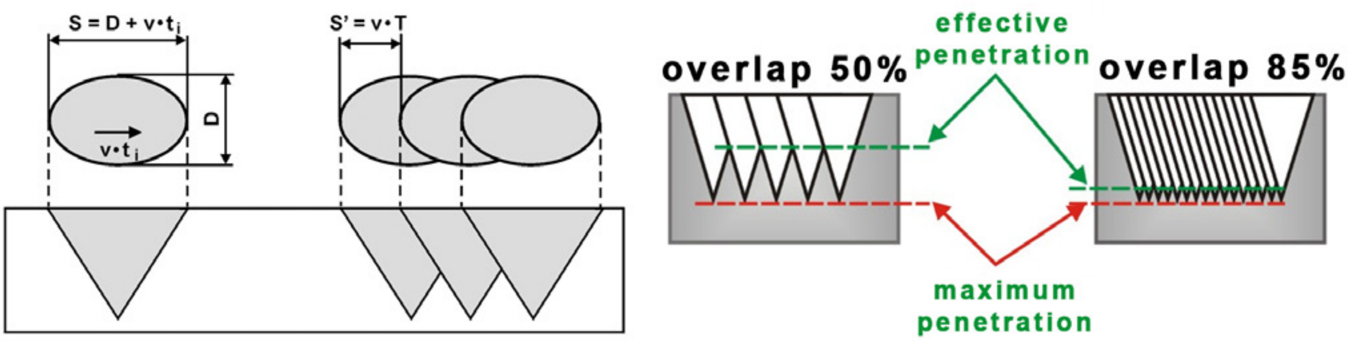


Fig. 3. Graphic interpretation of overlap of pulses of laser radiation beam: v – welding rate, t_i – pulse duration, D – diameter of area of focusing of radiation beam, T – pulse period [1,3]

In the pulsed laser welding process the most important issue is to ensure a slight heat impact unaccompanied by damage to the elements being joined yet accompanied by a metal-melting process. The requirements in question are met by the pulsed mode of laser operation, where relatively low average power of a radiation beam is accompanied by significant values of pulse power obtained for a very short (pulse) time. The action of a pulsed beam lasts only a few milliseconds. The molten material undergoes crystallisation before the occurrence of the next pulse. In this welding process a material is exposed to a number of pulses which melt a minimum volume of metal.

The short duration of a laser radiation beam pulse in the process of welding of such materials as medical steels (some austenitic acid resistant steels e.g. X15CrNiSi20-12 (1.4828)), titanium alloys (particularly Ti6Al4V applied in medicine), dispersion-hardened aluminium alloys, and galvanised steel, may be the reason for the formation of specific imperfections in welds and of the occurrence of some technological problems (medical steels and dispersion-hardened aluminium alloys – hot cracks, titanium alloys – hardening of the joint area, galvanised steels – evaporation of zinc, impeding the process of welding) [2].

It is emphasized [3,4,5] that the production of imperfection-free welds by means of a laser beam emitted in pulsed mode, particularly in the process of welding of precision elements, when, as a rule, the process of welding is carried out without adding a filler metal, is conditioned by the accurate selection of laser beam parameters. The production of a good quality weld depends on the power of the pulse (beam pulse action force) and its duration, the frequency of pulses and welding rate, the determination of the degree of overlap of the single welds formed by individual pulses of a laser beam, as well as the size of the area of a focused beam (active area), the location of the focus of the radiation beam in relation to the surface of material being welded, and the shape of a pulse.

On this occasion, one should also mention the significant impact of the shape of the pulse of a laser beam emitted in pulsed mode on the elimination of welding imperfections, in particular, hot cracks [3,4,5].

The focusing area is the active area of a laser beam in contact with the surface of an element being welded and is decisive for penetration depth and the width of the face of a weld. The power of a pulse represents the force with which a laser beam affects the inside of the focusing area. The higher the power of a pulse, the faster the heating of the material in the active area, though unfortunately also an increased risk of crack formation in the weld. The duration of a pulse represents the time of the action of an active radiation beam on a material, and thus is decisive for the volume of molten metal. The greater the amount of molten metal, the longer the heating and post-weld cooling times and the lower the tendency of crack formation in a weld.

An important parameter is the shape of a pulse, determining the time-related course of power changes within the area of a single pulse (Fig. 4). Many devices enable the emission of

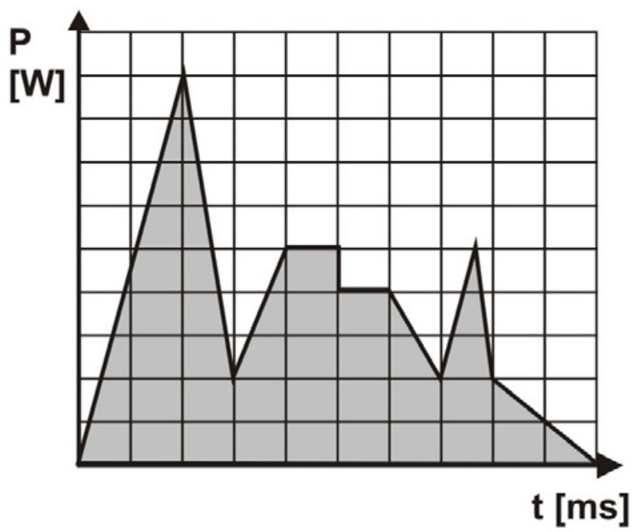


Fig. 4. Example of complex shape of laser radiation beam pulse

pulses up to several dozen milliseconds long, enabling simultaneous, almost steady, shaping of the course of power within the duration of a pulse i.e. shaping the division of pulse duration into time sub-areas (sectors) with very big density.

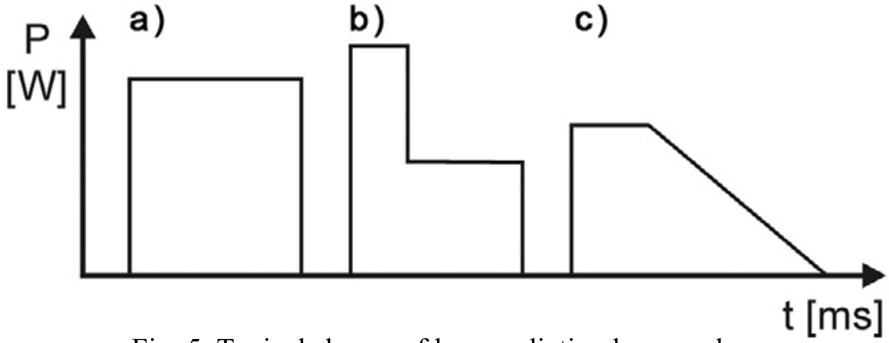


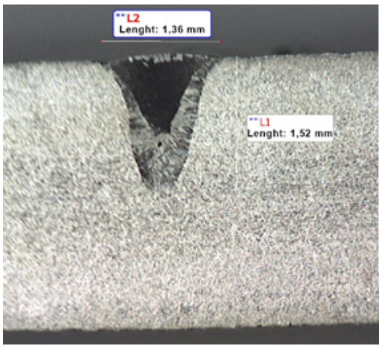
Fig. 5. Typical shapes of laser radiation beam pulse

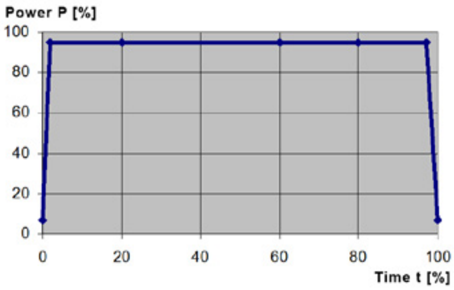
The complex shape of a pulse is the result of the division of the basic (rectangular) pulse into sectors of specific height and width. The length of each sector can be contained within the range of 0.3ms÷50ms with an increment of 0.1ms in the case of many precise laser welding machines. The height of each sector can adopt values from the range 0%÷100% of the specific power of a pulse.

The shape of a pulse should be optimised in relation to the basic physicochemical properties of the material being welded, in particular to the absorptivity of surfaces being processed. The most commonly applied shapes are simple rectangular pulses (Fig. 5a), rectangular pulses with a very short phase of high power and a long phase of low power (Fig. 5b) (applied while welding materials which strongly reflect radiation), and pulses with the gentle edge of radiation beam power decrease (Fig. 5c) (applied when the limitation of the dynamics of a welding thermal cycle is required e.g. in the case of materials susceptible to hot cracking).

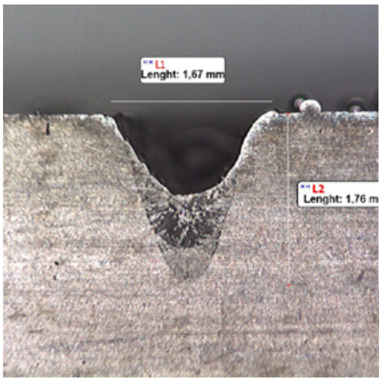
Appropriate shaping of a pulse through the composition of several phases adopting the form of a rectangular pulse and a pulse of edges of rising and falling power of a radiation beam can make it possible to produce proper joints without imperfections occurring in typical welding conditions.

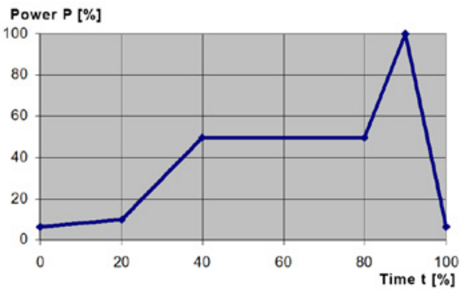
In the majority of typical cases it is the application of a rectangular pulse that makes it possible to obtain desirable results. As regards testing the impact of the parameters of YAG pul-



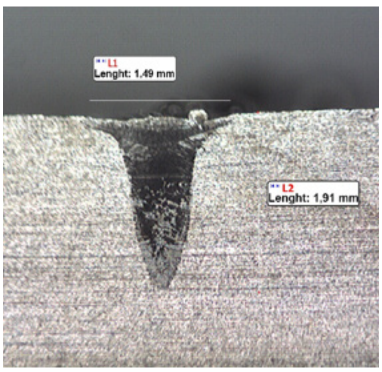


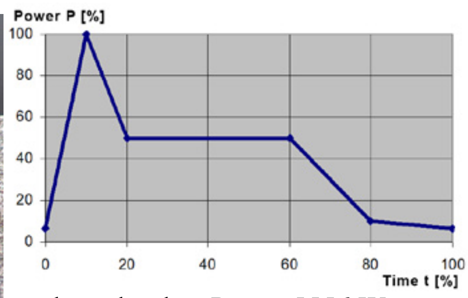
rectangular pulse, $P_{i\,max}$ =2250 W
penetration depth h=1.52 mm
face width s=1.36 mm





shaped pulse, $P_{i\,max}$ =5556 W
penetration depth h=1.76 mm
face width s=1.67 mm





shaped pulse, $P_{i\,max}$ =5556 W
penetration depth h=1.91 mm
face width s=1.49 mm

Fig. 6. Geometry of penetrations of steel X15CrNiSi20-12 made with laser beam emitted in pulsed mode with various pulse shapes; diameter of focusing area 0.8 mm, emission frequency 5 Hz, pulse energy 18 J, pulse duration 8 ms, welding rate 1.6 mm/s [2]

sed laser welding of various metals on the course of a welding process, research publications usually contain information about laser radiation beam pulses of a simple, rectangular shape. There are cases, however, when the application of a specific pulse shape improves the result of a welding process (enhanced seam appearance, elimination of welding imperfections). One may thus assume that the greater the density of the division of pulse duration into time sub-areas, the more effective the selection of an appropriate pulse shape (Fig. 4). The foregoing assumption allows more precise shaping of "the welding part of a pulse" and of "the control part of weld crystallisation" i.e. the function of the precise adjustment of the thermal effect of a radiation beam.

Through the application of a specific laser radiation beam shape one can modify the geometry of a weld. Figures 6, 7 and 8 present the penetrations of the steel X15CrNiSi20-12 acc. to PN-EN 10088-1 (mat. no. 1.4828, acc. to AISI – 309) made with a rectangular pulse laser beam at the Laboratory of Laser Technologies of Instytut Spawalnictwa. In addition to the penetrations, the previously mentioned figures also contain examples of pulses shaped by means of a device TruLaser Stadion 5004 equipped with an Nd-YAG laser of the maximum average power of a radiation beam of 95 W and the maximum power of a beam pulse of 6 kW [2]. The same welding parameters (pulse power, pulse duration, emission frequency and welding rate) were applied for both shaped and rectangular pulses.

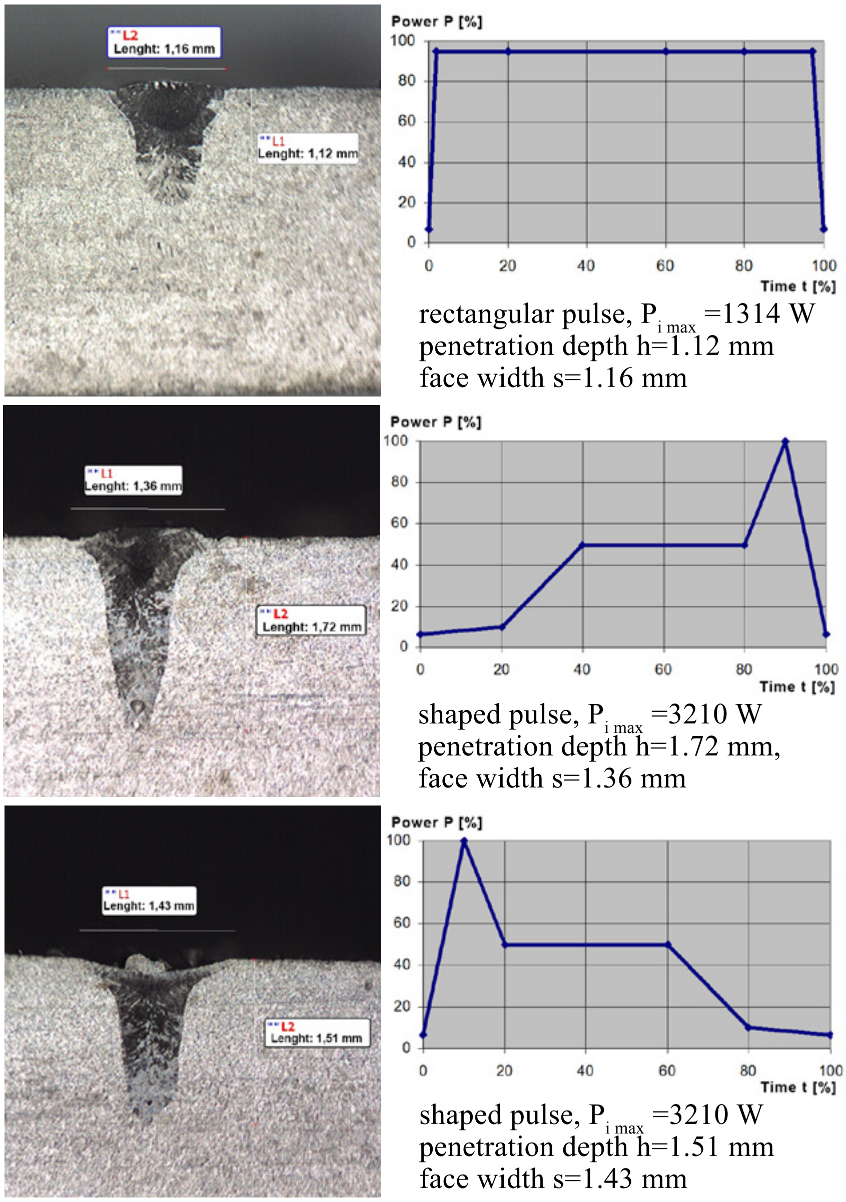
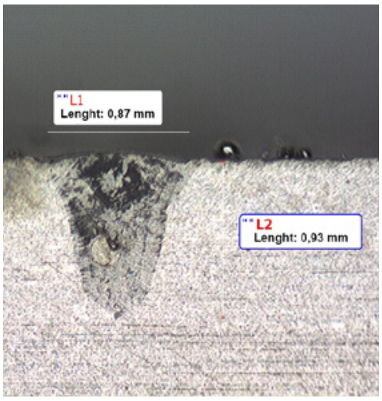
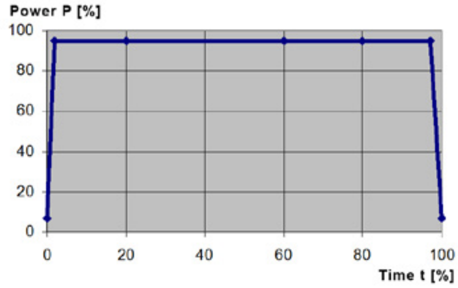


Fig. 7. Geometry of penetrations of steel X15CrNiSi20-12 made with laser beam emitted in pulsed mode with various pulse shapes; diameter of focusing area 0.6 mm, emission frequency 8 Hz, pulse energy 10.5 J, pulse duration 8 ms, welding rate 1.9 mm/s [2]

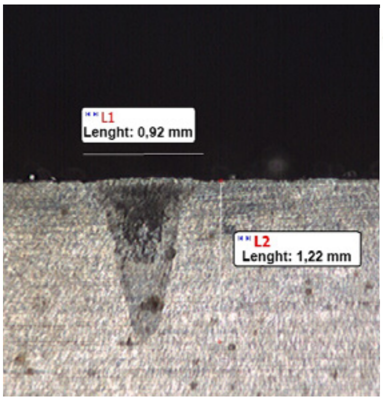
For a specific value of power and duration of a laser beam pulse having a basic rectangular shape, the average power of a pulse is similar to its maximum power, whereas in the case of a shaped pulse of the same energy (and average power), the value of the maximum power of a pulse is higher (Fig. 6), thus affecting the course of the formation of a weld.

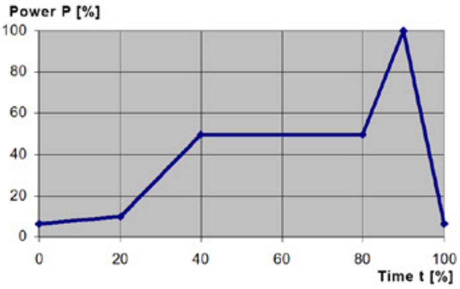
The replacement of a rectangular pulse with a shaped pulse of a prolonged edge of decreasing power resulted in a greater penetration depth and led to the advantageous modifica-



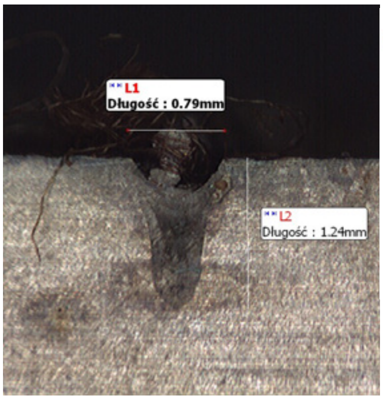


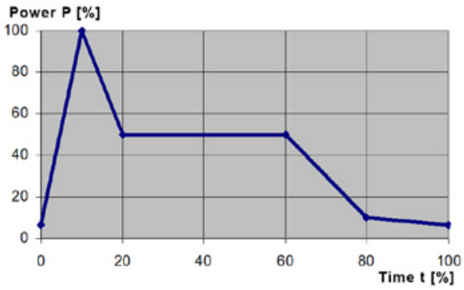
rectangular pulse, $P_{i\,max}$=702 W,
penetration depth h=0.93 mm,
face width s=0.87 mm



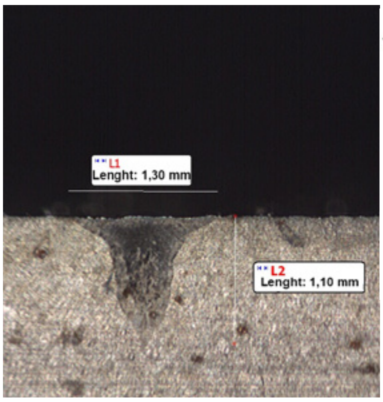


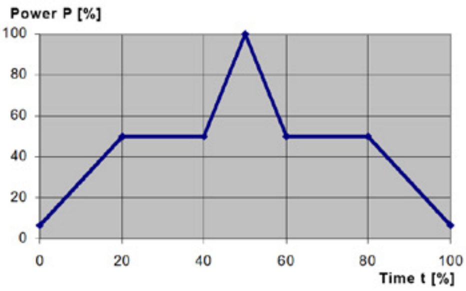
shaped pulse, $P_{i\,max}$ =1584 W,
penetration depth h=1.22 mm,
face width s=0.92 mm





shaped pulse, $P_{i\,max}$ =1584 W,
penetration depth h=1.24 mm
face width s=0.79 mm.





shaped pulse, $P_{i\,max}$ =1422 W,
penetration depth h=1.10 mm,
face width s=1.30 mm.

Fig. 8. Geometry of penetrations of steel X15CrNiSi20-12 made with laser beam emitted in pulsed mode with various pulse shapes; diameter of focusing area 0.3 mm, emission frequency 15 Hz, pulse energy 4.20 J, pulse duration 6 ms, welding rate 1.8 mm/s [2]

tion of the shape factor (Fig. 6). Impulses of a different shape having the same energy were responsible for the formation of incompletely filled grooves despite the fact that the power of the pulse was lower [2].

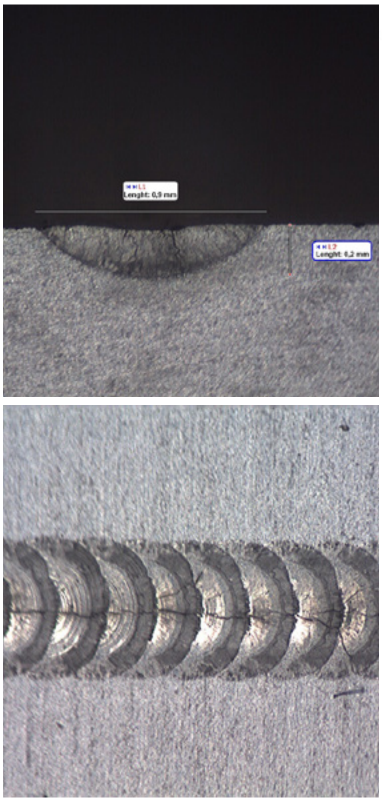
It should be noted that in conditions of high density of energy and high power of a pulse, only the modification of the direction of power increase or decrease at the beginning of a pulse may significantly modify welding conditions.

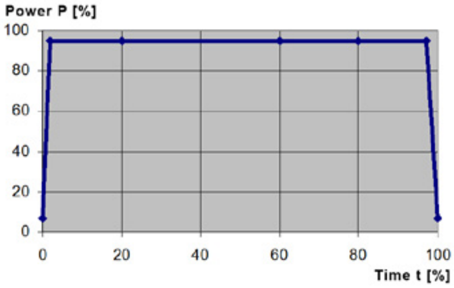
A pulse with an initial holding phase and an increase in power at the final phase is responsible for the gouging of the material, whereas an increase in power of the same value at the beginning of a pulse and further holding phase make it possible to obtain a properly-shaped weld.

These relations are different in the case of a radiation beam of different power density and pulse energy (Fig. 7, 8).

The appropriate shaping of a laser beam pulse may have a favourable effect on the geometry of a weld as well as positively affect the crystallisation of a weld. The foregoing is well exemplified by the melting (welding) of the aluminium alloy EN AW-5754 (EN AW-AlMg3). The penetrations (welds) made with a laser beam of a rectangular shape were characterised by the presence of clearly visible hot cracks (Fig. 9). The modification of the shape of a pulse enabled a significant reduction of these cracks (Fig. 10) [2].

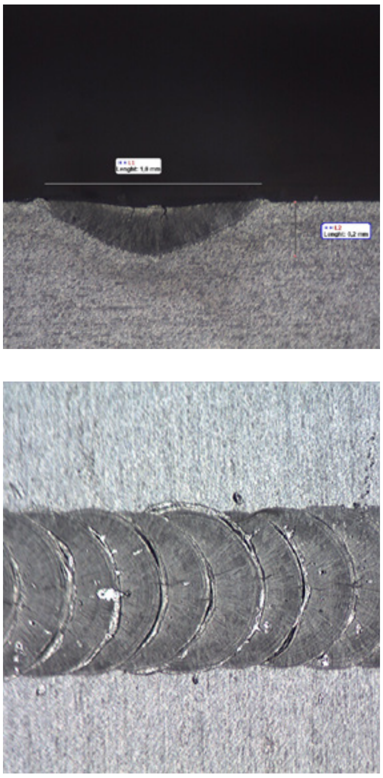
The laser welding of thin plates is often used to produce overlapping joints, ensuring high tolerance of the placing of elements being welded [6].

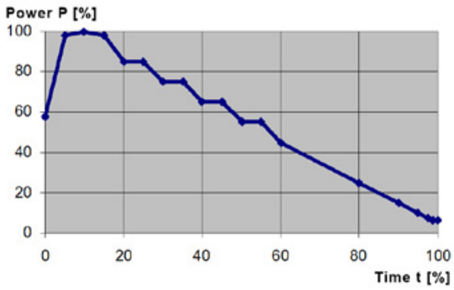




rectangular pulse, $P_{i\,max}$ =1752 W
penetration depth h=0,2 mm
face width s=0,9 mm

Fig. 9. Geometry of penetration of aluminium alloy EN AW-5754 (EN AW-AlMg3) made with laser beam emitted in pulsed mode of rectangular pulse shape; diameter of focusing area 0.8 mm, emission frequency 8 Hz, pulse energy 10,5 J, pulse duration 6 ms, welding rate 2,6 mm/s [2]





shaped pulse, $P_{i\,max}$ =3120 W
penetration depth h=0,2 mm,
face width s=1,0 mm

Fig. 10. Geometry of penetration of aluminium alloy EN AW-5754 (EN AW-AlMg3) made with laser beam emitted in pulsed mode of special pulse shape; diameter of focusing area 0.8 mm, emission frequency 8 Hz, pulse energy 10.5 J, pulse duration 6 ms, welding rate 2.6 mm/s [2]

The gas-dynamic passage (capillary) formed during laser welding should be stable enough to form a vent for zinc vapours being formed. The pressure of these vapours, however, is so high that it significantly hinders the formation of a proper weld. If in the structure of the joints of galvanised plates (i.e. proper projections) no special gaps for the removal of zinc vapours were provided, the weld interface between plates being joined becomes deformed and covered with imperfections in the form of gas pores, i.e. zinc vapours confined in the weld (Fig. 11). Zinc evaporates not only in the area of molten metal where metal is being molten but also in the heat affected zone heated as a result of a welding thermal cycle. For this reason, the intensity of the evaporation depends not only on the thickness of the coating of plates being joined but also on a welding thermal cycle.

In the process of laser welding using a radiation beam emitted in pulsed mode, the phenomena described above occurs with less intensity. A weld is formed by overlapping spot welds. The volume of liquid metal is smaller than in the case of laser wel-

The basic problem of these types of joints in relation to galvanised plates is the area of the contact of plates subjected to melting, in which the zinc layer undergoes melting followed by evaporation. The zinc vapours may become confined in the weld, forming numerous welding imperfections and deteriorating the quality of the joint.

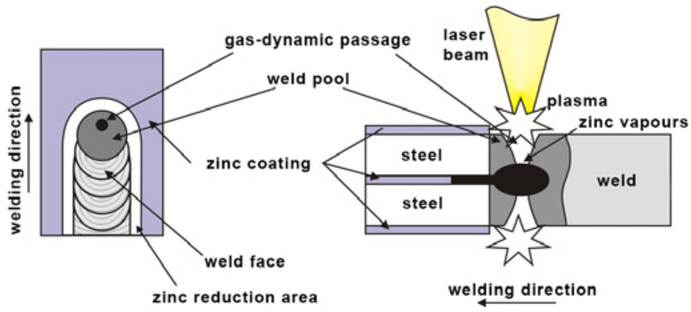
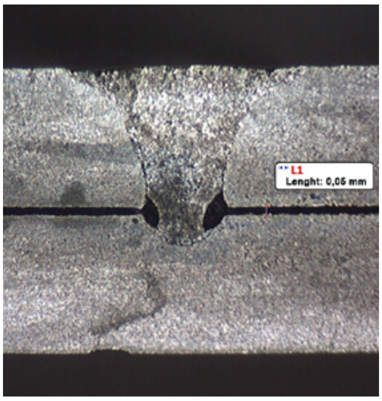
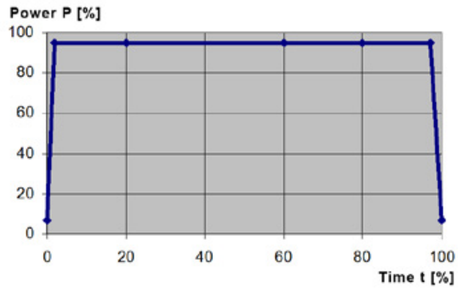
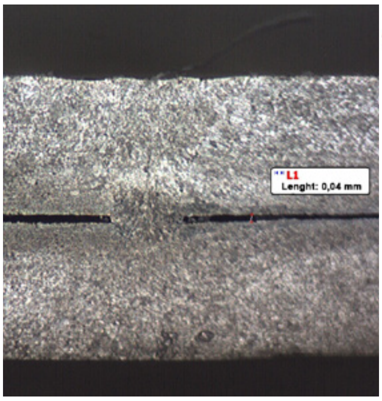


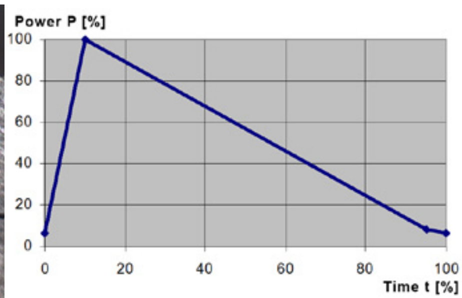
Fig. 11. Illustration of zinc evaporation zone in process of laser welding of galvanised plates placed to form overlap joint [7]





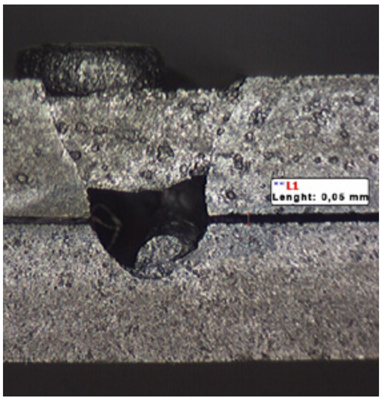
rectangular pulse, $P_{i\ max}$ =1752 W

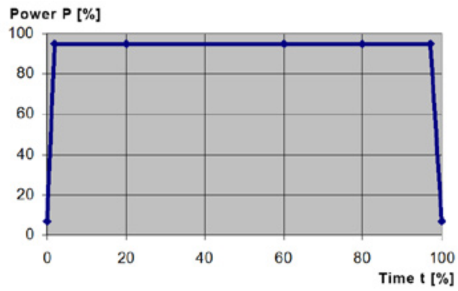




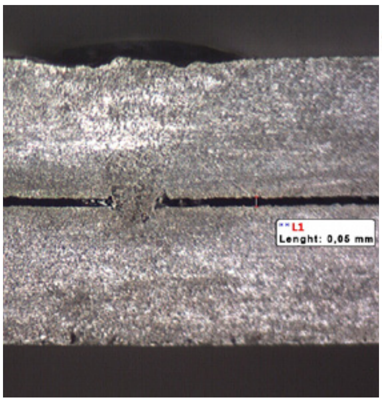
shaped pulse, $P_{i\ max}$ =3354 W

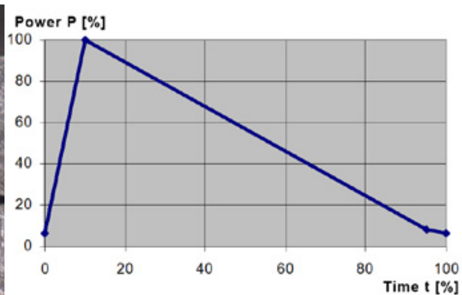
Fig. 12. Geometry of weld in overlap joint of plates of DX-53D steel, made with laser beam emitted in pulsed mode of various pulse shape; diameter of focus area 0.8 mm, emission frequency 8 Hz, pulse energy 10.5 J, pulse duration 6 ms, welding rate 2.6 mm/s [2]





rectangular pulse, $P_{i\ max}$ =2628 W





shaped pulse, $P_{i\ max}$ =5088 W

Fig. 13. Geometry of weld in overlap joint of plates of DX-53D steel, made with laser beam emitted in pulsed mode of various pulse shape; diameter of focus area 0.8 mm, emission frequency 8 Hz, pulse energy 10.5 J, pulse duration 4 ms, welding rate 2.6 mm/s [2]

ding using a continuous emission laser beam. The metal becomes molten and crystallised in a cyclical manner in accordance with the laser pulse emission frequency. The re-melting of part of a weld enables the off-take of confined zinc vapours. This re-melting is also facilitated by the appropriate modulation of the course of power throughout the duration of a pulse (pulse shape).

Figures 12 and 13 present the so-called "through welds" (formed by melting through one of the plates being joined) in overlap joints made of 3mm-thick cold-formed galvanised low-carbon steel DX-53D (acc. to PN -EN 10346:2009). Welds were made with a laser beam of a rectangular pulse and that of shaped pulses [2]. The contact gap between the plates being joined was 0.02mm÷0.04mm and provided inadequate off-take of zinc vapours while welding with a rectangular pulse. A favourable effect on the process of welding was obtained by applying laser beam pulses of a falling power curve at the final phase of a pulse.

Summary

The possibility of shaping the pulse of a laser radiation beam emitted in pulsed mode (i.e. the possibility of shaping changes in power within the duration of one pulse) is of significant importance particularly in laser welding of precision elements as it influences the amount of heat supplied to the material. A specific laser beam shape enables precise supply of energy in one pulse, particularly through defining the value and location of the peak power sector of a pulse. The shape of a laser beam pulse influences the geometry of a weld and the conditions of weld crystallisation. The manner of this influence varies depending on materials, their chemical composition and state of delivery. Changing a pulse shape can help limit or eliminate welding imperfections characteristic of some metals and their alloys. The selection of pulse shape is conditioned by the rate of the change of power in time, particularly in a pulse section of descending characteristic. Pulses of complex characteristic in the area of gradual power decrease may prove their usability in the welding of numerous materials.

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