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# Applicability of Laser Welding in the Joining of Cast Elements of the Combustion Engine Manifold and Turbine.

## Part 2. Laser Welding of the Compensating Capsule with the Collector

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**Abstract:** The article presents attempts related to the laser welding of combustion engine manifold and turbine. The study discussed in the article made it possible to identify the potential and limitations connected with the application of laser welding technologies, workmanship accuracy and the positioning of elements to be welded. The study-related tests enabled the assessment of the effect of primary welding parameters on the shape of the weld both in terms of keyhole and melt-in welding processes. The first part of the research-related article discusses results concerning the laser welding of the compensating capsule with the collector.

**Keywords:** laser welding, combustion engine, manifold, turbine

**DOI:** [10.17729/ebis.2020.3/4](https://doi.org/10.17729/ebis.2020.3/4)

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### Introduction

Laser welding is a process, where the energy of a monochromatic concentrated light beam is absorbed by and melts materials to be joined. Present-day designs of solid-state lasers, i.e. disc lasers, fibre lasers (the length of an emitted electromagnetic wave amounting to approximately 1  $\mu\text{m}$ ) and  $\text{CO}_2$  (gas) lasers (where the length of an emitted electromagnetic wave is 10.6  $\mu\text{m}$ ) enable the obtainment of very high power density in an area affected by the laser beam. As a result, it is possible to obtain significant penetration depth and high welding rates. Welding linear energy (i.e. laser beam power-welding rate ratio) is significantly lower in comparison with that accompanying arc welding methods. At the same time, the welding process efficiency is higher. The welding

process is usually performed without the use of the filler metal and the weld formation results from the melting of the edges of materials being joined. If the density of power is high (e.g. in keyhole welding), the weld is narrow and deep. For this reason, it is essential to accurately and repeatedly match elements to be welded so that the laser beam can always affect the interface between the elements. If the density of power is lower, usually obtained through the defocusing of the laser beam, it is possible to perform the melt-in welding process. In such a case, the depth of penetration is significantly shallower (if compared with that obtained in keyhole welding), whereas the weld is considerably wider. In terms of the shape, laser welds obtained using lower power density are similar to those obtained using arc welding techniques

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and are characterised by the very high aesthetics of the weld face. Similar to keyhole welding, the above-named method does not require the use of the filler metal, yet it is important to ensure that elements to be welded are matched precisely and without a gap in between. The selection of a given laser welding technique depends primarily on requirements related to joints, i.e. primarily the penetration depth and the geometry of the interface between the elements to be joined [1–4].

The manifold unit in combustion engines is a complex element characterised by a complicated shape. Usually, the manifold is made by welding several sheet metal elements and tubes composing ultimately a monolithic structure. The making of the manifold is both time-consuming and costly and the cross-section of obtained ducts is primarily limited by component elements. The above-presented problems inspired attempts at replacing sheet metal elements with cast ones, which, in relation to welded elements, should translate into savings in time and manufacturing costs as well as could lead to the greater diversity of obtained cross-sectional shapes. The manifold unit is composed of three steel castings joined by means of compensating capsules. Primary difficulties accompanying the making of welded joints in the above-named unit are the following:

- significantly varying thicknesses of elements to be joined (casting wall is significantly thicker than the thickness of the compensating capsule),
- necessity of maintaining the position of outlet duct flanges in one plane, resulting in significant difficulties accessing an area to be welded around the entire circumference of elements,
- necessity of preventing the excessive melt-through of elements being joined (particularly in relation to compensating capsules),

– more difficult, in comparison with that of steel elements, the welding cast steel elements.

The collaboration with the industrial partner involved tests concerning the use of various arc welding and laser welding methods for the joining of manifold elements. The primary requirements related to the above-named elements is the obtainment of appropriate strength and, primarily, the integrity of the joint, the lack of the penetration of the compensating capsule wall and the minimum post-weld contamination of the elements. This article discusses results of tests concerning the use of laser welding for the joining of manifold elements.

### Test rig and materials

The technological tests concerning the laser welding of manifold elements involved the use of a robotic station including a KUKA KR30HA industrial robot, a DKP-400 tilting turntable and a TruDisk 12002 industrial solid-state laser having a maximum laser beam power of 12 kW (Fig. 1). The tests also involved the use of a D70 optical system equipped with a collimator lens having focal length  $f_{kol} = 200$  mm and a focusing lens having focal length  $f_{og} = 400$  mm. TruDisk 12002 was connected with the D70 head with an optical fibre having a diameter of 400  $\mu$ m. As a result, the laser beam focus diameter amounted to 0.8 mm

The cast steel elements were made of material grade 1.4848, whereas the compensating capsules

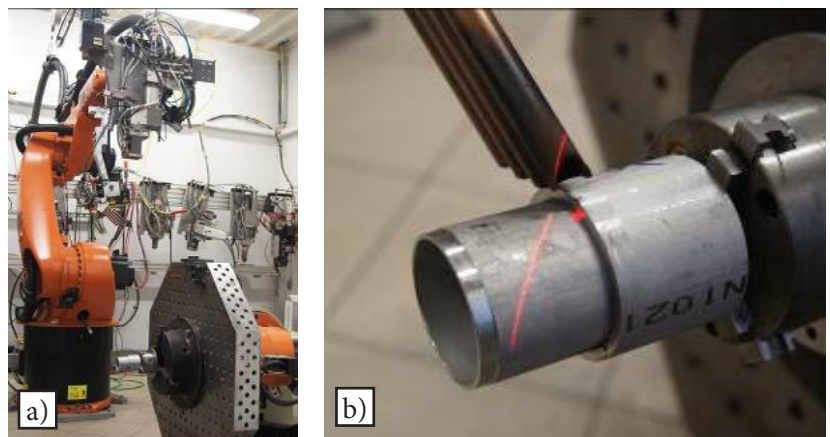


Fig. 1. Robotic laser welding test rig (a) and the test element in the welding manipulator (b)

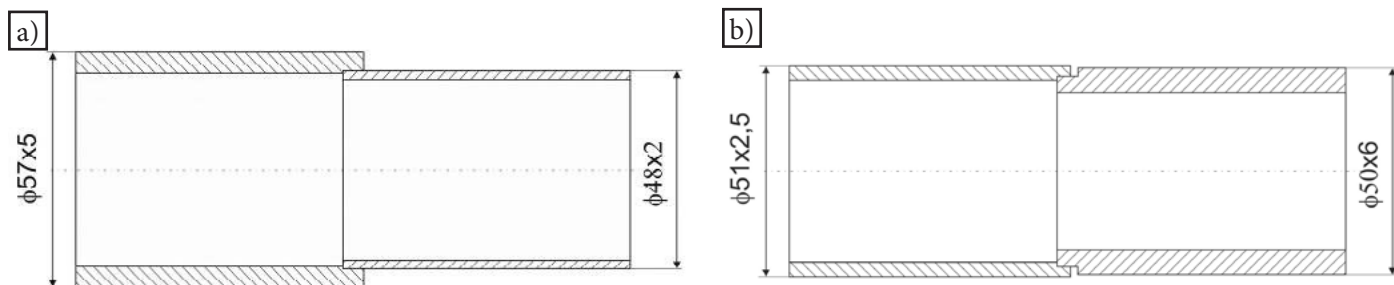


Fig. 2. Schematic diagrams of the joints representing the welded joints of the manifold unit: a) turbine-capsule joint, b) capsule-collector joint

were made of material grade 1.4828 and 2.4856. For research purposes, the industrial partner provided the test joint elements representing actual welded joints (steel casting + compensating capsule) (Fig. 2). The accuracy of the preparation of the test elements reflects the accuracy and tolerances connected with the matching of actual elements (designed as arc welded elements). Figure 2 presents sketches of welded joints in the manifold. Before welding, the test elements were tacked using the pulsed laser.

### Joint of the compensating capsule with the collector

The interface of the elements to be joined, i.e. the compensating capsule and the collector, results from the complex design of the capsule. In currently used compensating capsules, there is a gap in the interface area (simulated in test

joints, Fig. 2b). The presence of the gap constituted a significant problem also in relation to the positioning (inclination) of the laser beam (Fig. 3a) as well as the assessment of the shape and the strength of the weld. In terms of laser welding, the most favourable solution should involve the preparation of the capsule where the capsule was fully adjacent to the collector, i.e. without a gap (Fig. 3b). The welding tests were performed in relation to the initial version of the compensating capsule and the modified version adapted for the laser welding process.

The welding tests concerning the joining of the compensating capsule and the collector were performed in relation to various welding parameters (Table 1). The weld faces are presented in Figure 4, whereas the macrostructures of the welds (two macrostructures per one joint) are presented in Figure 5.

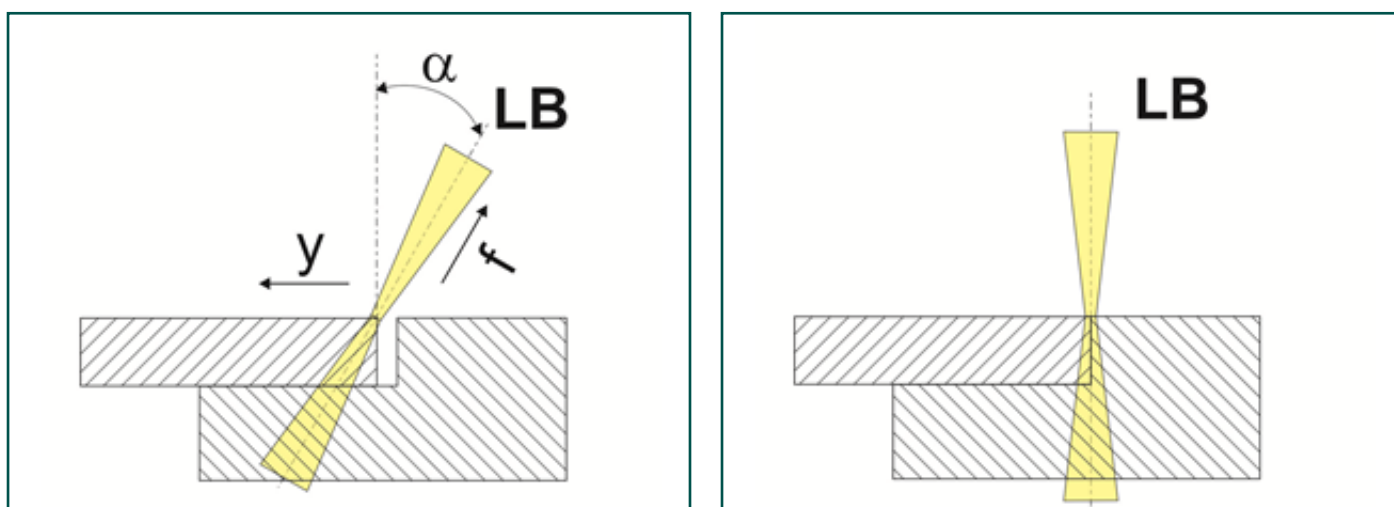


Fig. 3. Schematic diagram presenting the position of the laser beam at the interface of the elements subjected to welding (compensating capsule - collector) in relation to two variants of the preparation of the edges of the elements with marked geometric parameters characterising the position of the laser beam focus in relation to the visible edge of the interface;  $\alpha$  - angle of the inclination of the laser beam propagation direction,  $f$  - position of the laser beam focus along the axis of the laser beam propagation (laser beam defocusing degree),  $y$  - shift of the laser beam focus towards the visible edge of the interface of the elements being joined in the direction parallel to the axis of symmetry of the turbine and compensating capsule

Table 1. Laser welding parameters obtained in the joint of the compensating capsule with the collector;  
preparation of the joint as in Fig. 3a

Specimen no.	Laser beam power $P$ , W	Welding rate $v$ , m/min	Angle $\alpha$ , °	Defocusing $f$ , mm	Shift $y$ , mm
21	2500	1,5	0	0	0
22	2500	1,5	0	0	1
23	3500	1,5	0	0	1
24	3500	1,5	0	0	5
25	3000	1,5	0	0	5
26	2500	1,5	0	0	5
31	3500	0,94	0	30	0
32	4500	0,94	0	30	0
33	2500	1,5	20	0	0
34	2500	1,25	20	10	0
35	3000	1,25	20	10	0
36	3000	1,08	20	20	0

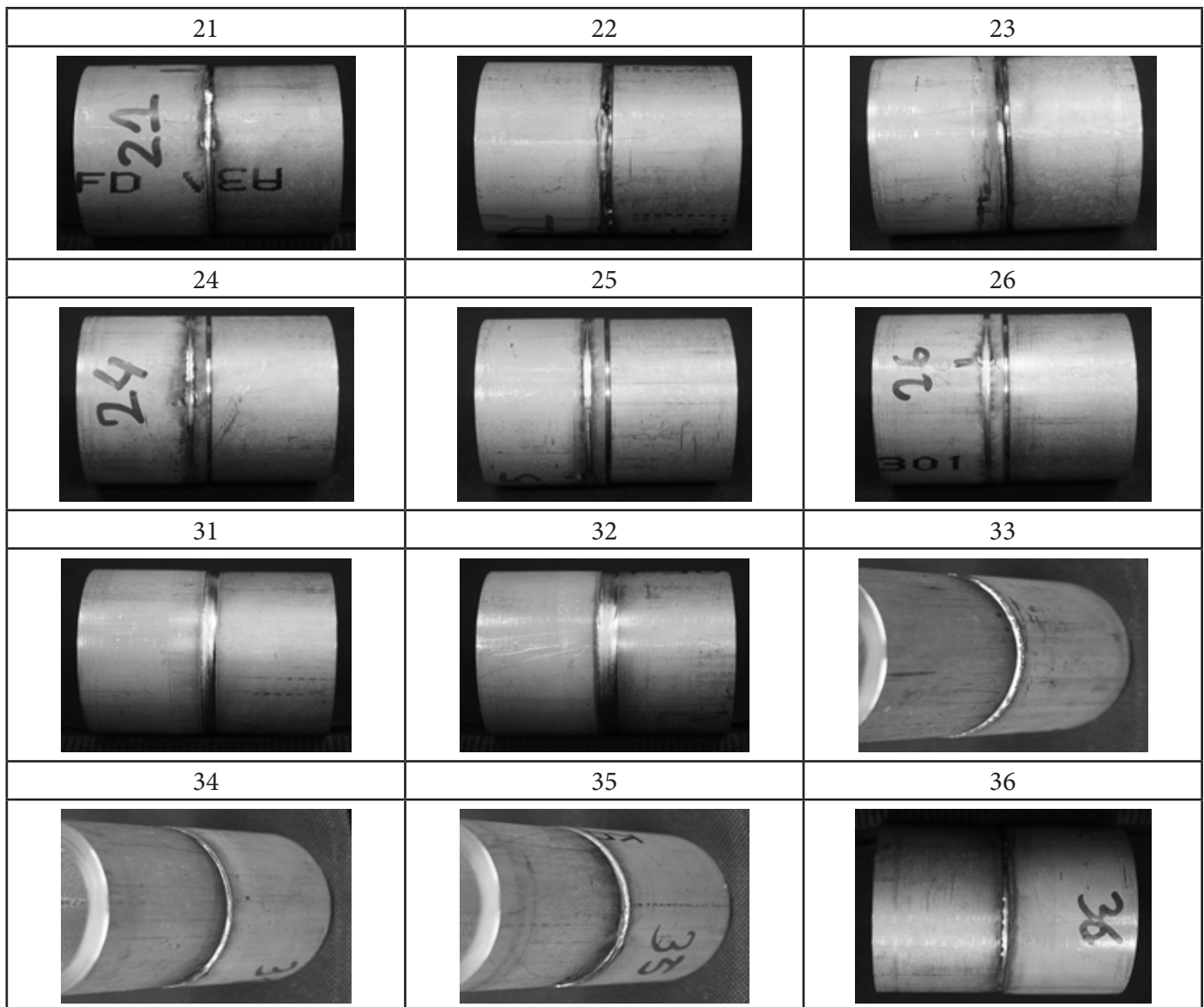


Fig. 4. Weld face in the laser welded joint of the compensating capsule with the collector;  
welding parameters as in Table 1



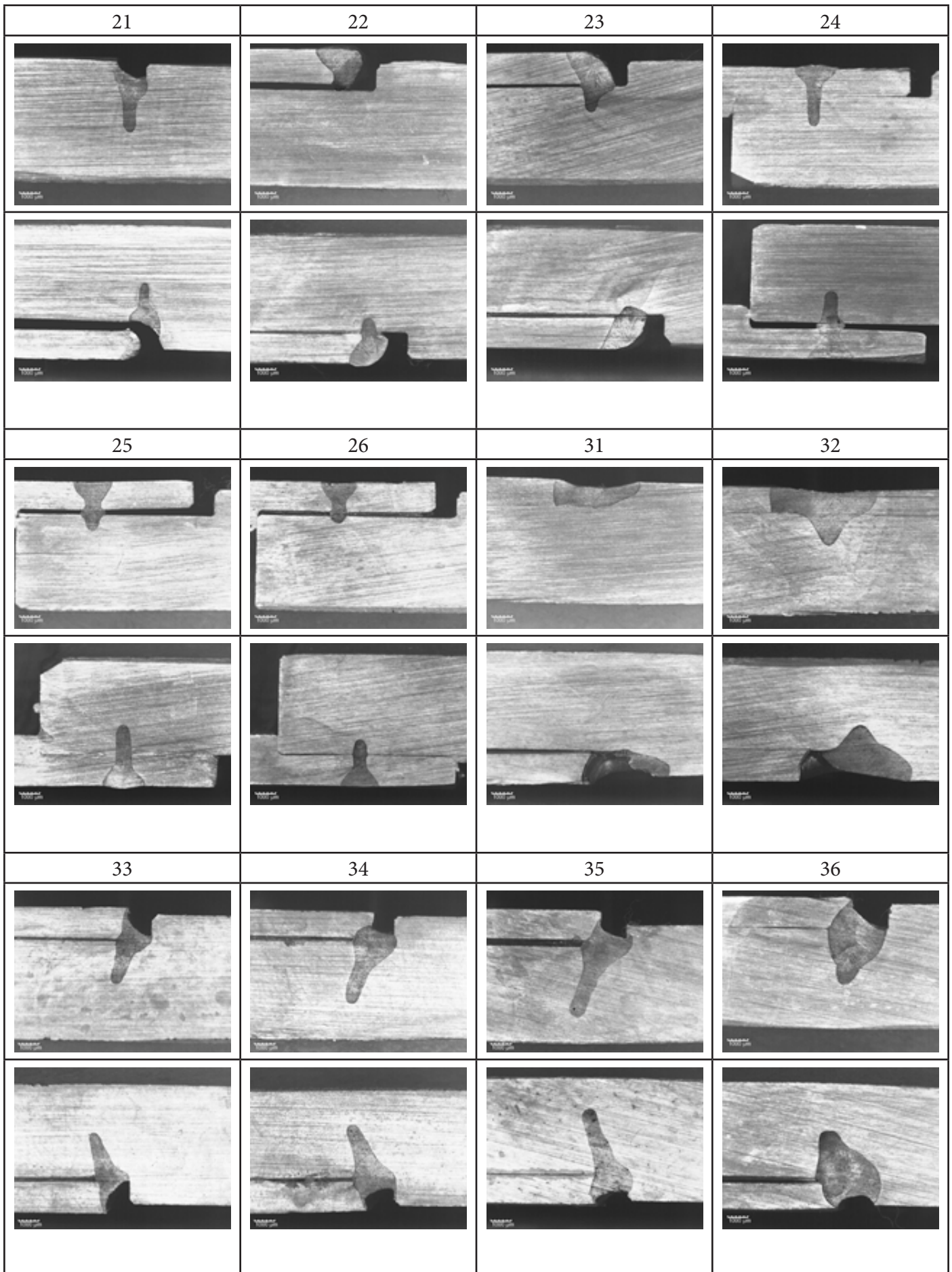


Fig. 5. Macrostructures of the laser welded joints of the compensating capsule with the collector; parameters as in Table 1

The preparation of the elements to be welded as presented in Figure 3a and the accuracy of their matching (characteristic of cast elements) were responsible for the fact that the adjustment of welding parameters enabling the obtainment of a proper weld was very difficult as well as for the fact that the welding process was not repeatable.

First welding tests were performed using the laser beam focused on the edge of the capsule and inclined at angle  $\alpha=0^\circ$  (Fig. 3a). Welding area metallic continuity was obtained within the area where the capsule wall was adjacent (properly) to the collector socket (Fig. 5, macrostructure 21). The weld was concave, which resulted from the preparation of the elements to be welded. The lack of the adherence of the capsule edge to the collector socket resulted in the formation of a groove between the capsule and the collector. The lack of the filler metal during the laser welding process precluded the filling of the groove. The laser beam melted the capsule edge and penetrated the collector socket. On the opposite side of the cut plane it was possible to observe a significant gap between the capsule and the collector. The laser beam melted the capsule edge and penetrated the collector socket, yet, the excessively large gap precluded the joint of the liquid metal of the capsule edge and collector socket. Subsequent laser welding tests were performed by shifting the laser beam focus by  $y = 1$  mm from the capsule edge (Fig. 3a). The shifting of the laser beam away from the capsule edge aimed to obtain the greater volume of the molten capsule edge, which could be used as the filler metal to make a quasi-fillet weld. Because of the variable gap between the elements it was necessary to increase the power of the laser beam. The use of a laser beam power of 2500 W did not enable the obtainment of a uniform and continuous weld around the entire circumference of the joint (Fig. 5, macrostructure 22). At the same time, in the areas of weld continuity and within the groove bottom area, the molten material

flowed towards the collector socket forming a characteristic overlap (imperfection 506 in accordance with PN-EN ISO 6520). The proper assessment of the above-named imperfections requires the metallographic specimen. An increased power of 3500 W enabled the obtainment of weld integrity around the entire joint circumference (Fig. 5, macrostructure 23). Differences in the weld shape observed on the opposite sides of the cross-section resulted from the variable gap in the joint area and the accumulation of heat accompanying the closure of the girth weld.

Moving the laser beam focus by  $y = 5$  mm away from the capsule edge enabled the obtainment of an aesthetic wedge weld continuous around its entire circumference in the overlap joint (terminology in accordance with PN-EN ISO 2553). The above-presented configuration was used in the welding tests performed in relation to three values of laser beam power, i.e. 2500 W, 3000 W and 3500 W (Fig. 4, images 24–26 and Fig. 5, macrostructures 24–26). In the above-named case, the part of the weld responsible for the transmission of loads was the interface of the overlapping elements (dimension  $w$ , Table 2) and not the depth of penetration  $b$  into the collector wall. Nevertheless, welding parameters should be adjusted in a manner ensuring the integrity of the joint (obtained through penetration into the collector) also in relation to variable matching parameters (gap  $g$ ) or other, momentary, process disturbances. Each of the adjusted power levels enabled the obtainment of penetration into the collector wall and the integrity of the joint. An increase in laser beam power was accompanied by an increase in the depth of weld penetration into collector wall  $b$ , where the smallest differences in the depth of penetration into the collector wall at the opposite cross-sections of the weld ( $b_1 = 1.46$  mm and  $b_2 = 1.59$  mm) were obtained in relation to a maximum power of 3500 W used in the tests (Fig. 6). The width of the weld at the interface of the

joined elements to a lesser degree depended on applied laser beam power (Fig. 7). In terms of a gap of less than 0.1 mm, regardless of laser beam power, weld width  $w$  was restricted within the range of 0.72 mm to 0.82 mm. Weld width  $w$  was significantly more affected by gap size  $g$  between the wall of the capsule and the collector. In relation to the joint made using a laser beam power of 3500 W, the width of the weld at the interface of the capsule and collector was  $w_1 = 0.75$  mm in relation to gap  $g_1 = 0$  mm and  $w_2 = 1.34$  mm in relation to gap  $g_1 = 0.32$  mm. As regards the welding of elements matched with a gap, during the welding process, the liquid metal of the weld tended to

slightly flow between elements being welded, thus extending the melted area of plate surfaces at their potential interface. However, when matching elements before welding the gap size should be as small as possible (slide fit), which significantly improves the repeatability of the welding process and reduces the risk of porosity formation in the melted interface area.

Inclining the laser beam (angle  $\alpha$ ) and moving the focusing area outside the capsule edge resulted in the obtainment of significant freedom in terms of the repeatability of laser beam positioning along the  $y$ -axis (see Fig 3a). Slight shifts towards the  $y$ -axis did not affect the quality and functional properties of the joint.

Table 2. Characteristic dimensions of wedge welds in the overlap joint

No.	P [kW]	$h_1$ [mm]	$h_2$ [mm]	$w_1$ [mm]	$w_2$ [mm]	$g_1$ [mm]	$g_2$ [mm]	$b_1$ [mm]	$b_2$ [mm]
1	2.5	2.08	2.31	0.91	0.72	0.18	0.07	0.36	0.73
2	3.0	2.45	3.01	1.17	0.82	0.19	0.00	0.81	1.48
3	3.5	2.96	3.42	0.75	1.34	0.00	0.32	1.46	1.59

measurement diagram:

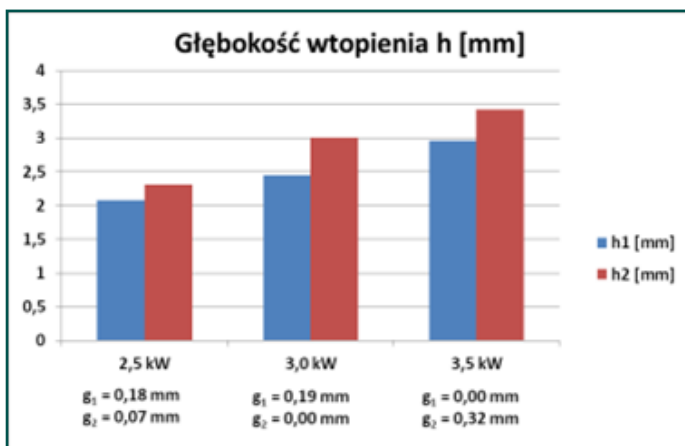
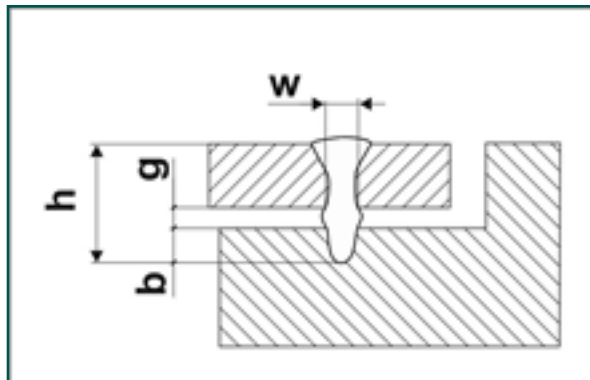


Fig. 6. Effect of the laser beam power and the gap between welded elements on the penetration depth  $h$  in the overlap laser welded joint

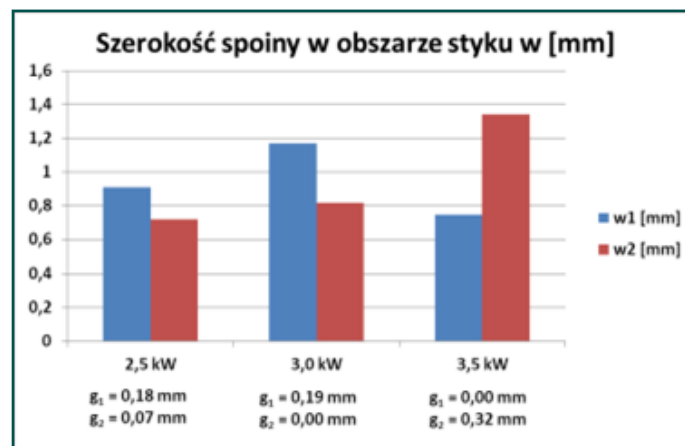


Fig. 7. Effect of the laser beam power and the gap between welded elements on the joint width  $w$  in the interface of the elements to be joined by overlap laser welding



Tests involving the defocused laser beam inclined at angle  $\alpha = 0^\circ$ , the melting of the larger area of the joints and filling the existing gap did not produce the expected result. In spite of the aesthetically “spread” weld face in the remaining areas (Fig. 4, images 31–32), the welding process was accompanied by disturbances affecting the weld pool (locally and uncontrollably), resulting in the lack of penetration (Fig. 5, macrostructure 31–32).

The research also included tests involving changes in the laser beam inclination angle and/or the defocusing of the laser beam. Angle  $\alpha = 20^\circ$  seemed the most favourable position as regards the matching of the compensating capsule and the collector with the gap (Fig. 3a). Regardless of the gap between the capsule and the collector it was possible to obtain the weld continuity around the entire circumference (Fig. 5, macrostructure 33–36). Among the test welds, the most convenient joints were those made using higher linear energy (Fig. 5 macrostructure 20) where the laser beam was defocused to  $f = 20$  mm and it struck the surface at angle  $\alpha = 20^\circ$ .

An unsolved issue related to the above-named type of joint is the determination of the weld size which could act as a measureable

parameter determining the strength and quality of the weld. Because of the fact that the joint between the compensating capsule and the collector, due to the manner of positioning, is primarily exposed to shear, a reasonable solution might involve the measurement of the penetration length along the axis of the interface between the joined elements.

As regards the laser welding process, the simplest solution involved the matching of the elements without the gap (Fig. 3b). In the above-named case, the butt weld was formed and the primary criterion determining the quality of the joint was the obtainment of the entire melting of the compensating capsule front and the edge of the collector socket. The parameters of the welding process used in relation to the joint of the compensating capsule with the collector matched without the gap are presented in Table 3. The weld face is presented in Figure 8. The macrostructures of the obtained welds (two macrostructures in relation to the joint) are presented in Figure 9.

The performed laser welding tests involving the compensating capsule and the collector matched without the gap demonstrated that the above-named method of matching was the most favourable in relation to the laser welding

Table 3. Parameters of the laser welding of the compensating capsule and the collector matched without the gap

Specimen no.	Laser beam power $P$ , W	Welding rate $v$ , m/min	Angle $\alpha$ , °	Defocusing $f$ , mm	Shift $y$ , mm
41	2500	1.5	0	0	0
42	3000	1.5	0	0	0
43	3500	1.5	0	0	0
44	4000	1.5	0	0	0

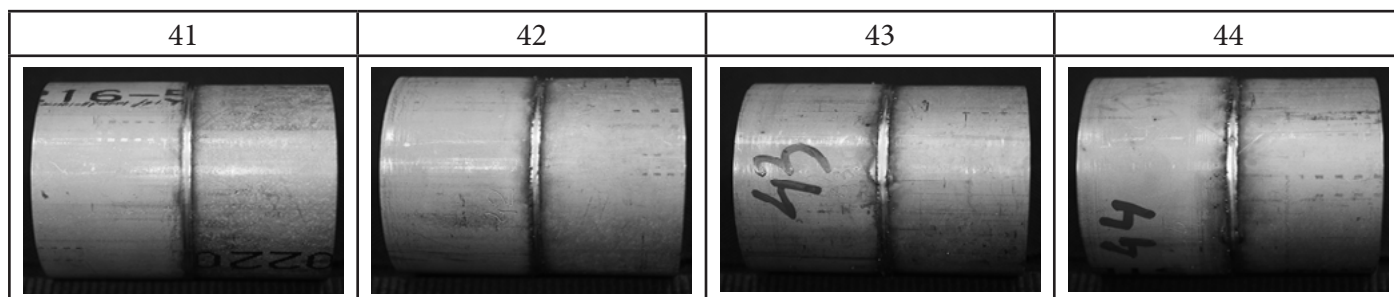


Fig. 8. Weld face in the laser welded joint of the compensating capsule with the collector; welding parameters as in Table 3



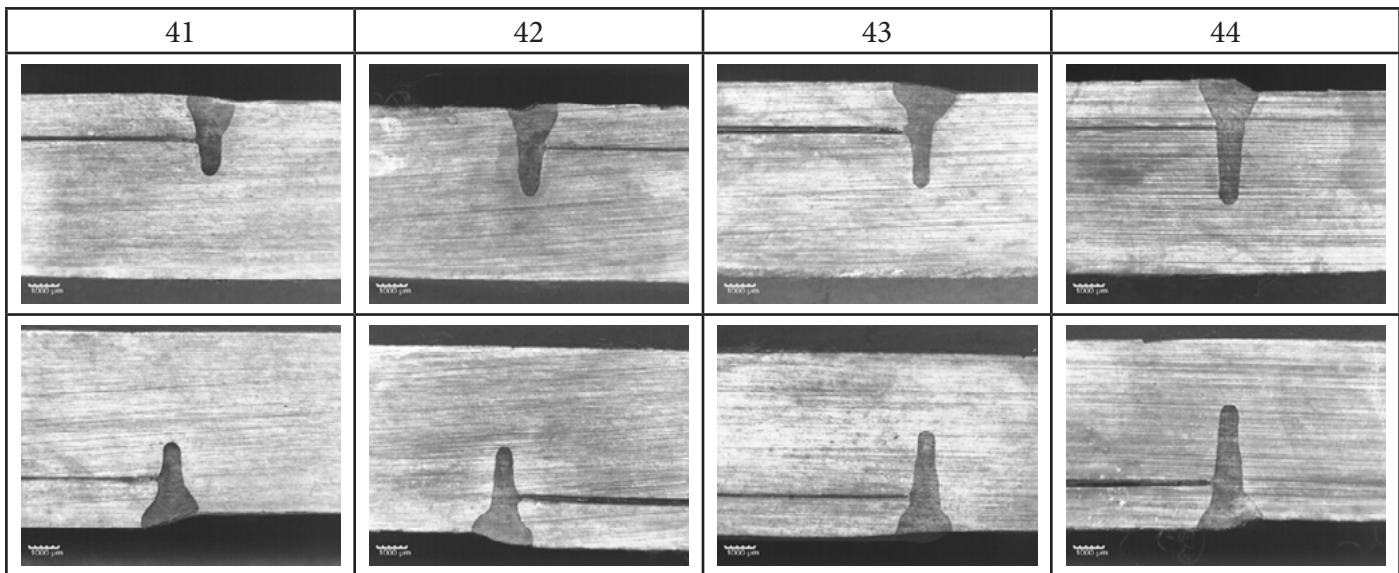


Fig. 5. Macrostructures of the laser welded joints of the compensating capsule with the collector; parameters as in Table 3

process. The full penetration of the capsule wall was obtained regardless of applied laser beam power (Fig. 9). An increase in laser beam power resulted in the increased depth of penetration into the collector socket. The aforesaid increase in penetration depth did not affect the strength of the joint. Laser beam power restricted within the range of 2.5 kW to 3.0 kW (parameters 41 and 42, Table 3) was sufficient to melt the capsule wall and penetrate the collector socket. In the above-named configuration, gap  $g$  between the capsule wall and the collector socket did not significantly affect the welding process (on condition that the gap was free from impurities).

### Summary

The obtainment of proper and repeatable laser welded joints of the turbine with the compensating capsule proved difficult. The aforesaid difficulty resulted directly from the design and dimensional accuracy of the elements to be joined as well as from the location of welds. In some cases, the randomly matched elements of the turbine and the capsule enabled the proper welding of the well-matched elements (i.e. without a gap) and the obtainment of a good quality joint. In other cases, the elements were matched “loosely”. At the initial stage of the welding process, when the tolerance of the

matching of the collector socket and the compensating capsule was excessively high, the formation of the weld went on “smoothly”. Because of the weld contraction and the loose match of the elements on the other side of the joint, the gap increased and, as a result, the welding process was disturbed, leading to the formation of local imperfections (concavities, weld discontinuities). It was stated that activities aimed at improving the stability and repeatability of the laser welding process of the above-named element should involve changes in technologies used to manufacture elements to be welded. However, the implementation of such changes in the design of the compensating capsule and/or the collector as well as the narrowing down of tolerances related to the workmanship of such elements (aimed at their better match) might significantly increase the cost of elements to be welded or even prove impossible (e.g. because of the interaction of such elements with specific combustion engines). In addition, the performance of the proper welding process requires the appropriate access of the laser head enabling the positioning of the laser beam focus at the interface of elements being welded. The aforesaid access cannot be impeded by the systems fixing and positioning elements to be welded or, directly, by the complex shape of such elements.

The above-presented tests led to the conclusion that in terms of the laser welding of the compensating capsule with the collector the most favourable solution involves the modification of the capsule design and the performance of the welding process as presented in the diagram shown in Figure 3b.

***The research-related tests were financed within the project “The Development of Innovative Arc and Laser Welding Technologies and the Identification of their Effect on Emission into the Atmosphere and Work Environment” (no. POIR.01.02.00-00-0210/16), conducted within Measure 1.2 Sectoral R&D Programmes (INNOMOTO) of the Operational Programme Smart Growth 2014-2020 and co-financed by the European Union from the resources the European Regional Development Fund.***

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