

Sebastian Stano, Radomir Anioł

# Applicability of Laser Welding in the Joining of Cast Elements of the Combustion Engine Manifold and Turbine. Part 1. Laser Welding of the Turbine with the Compensating Capsule

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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 turbine with the compensating capsule.

**Keywords:** laser welding, manifold

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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

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Sebastian Stano, PhD (DSc) Eng. – Łukasiewicz – Instytut Spawalnictwa Gliwice, Zakład Technologii Spawalniczych /Welding Technologies Department/; Radomir Anioł – Sonima Group

density are similar to those obtained using arc welding techniques 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),
- in comparison with steel elements, the more problematic welding of cast elements.

The research discussed in this article and performed in conjunction with an industrial partner involved tests concerning the application of various arc welding methods and laser welding methods to join the elements of the manifold unit. The primary requirements concerning joints in the manifold include appropriate leak-tightness, the lack of pressure capsule wall penetration and minimum post-weld contamination of the elements. The article discusses the results of tests concerned with the use of laser welding to join the elements of the manifold unit.

## Test rig and materials

The technological tests of the laser welding of the element of the manifold unit were performed using a robotic station including a KUKA KR30HA industrial robot, a DKP-400 tilting turntable and a TruDisk 12002 solid-state industrial laser having a maximum power of the laser beam on the material of 12 KW (Fig. 1). The tests also involved the use of working optics (D70) equipped with a collimator lens having focal length  $f_{kol} = 200$  mm and a focusing lens having focal length  $f_{og} = 400$  mm. The TruDisk 12002 laser was connected with the D70 working head with an optical fibre having a diameter of 400  $\mu\text{m}$ , which enabled the obtainment of the laser beam focus having a diameter of 0.8 mm.

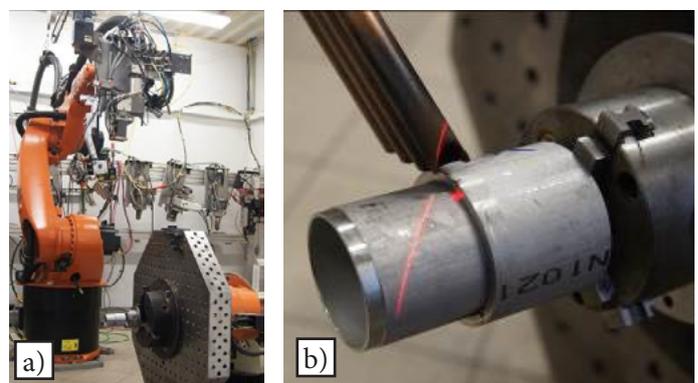


Fig. 1. Robotic laser welding test rig (a) and the test element in the welding manipulator (b)

The cast steel elements were made of cast steel grade 1.4848, whereas the compensating capsules were made of material grade 1.4828 and 2.4856. For test-related purposes, test elements

of the joint provided by the industrial partner represented actual welded joints (steel casting + compensating capsule) (Fig. 2). The accuracy of the preparation of the test element represented the accuracy and the tolerances applied when matching actual elements designed as arc welded element. Figure 2 presents the schematic diagram of joints representing the welded joints of the manifold unit. Before welding, the test elements were tacked using the pulsed laser.

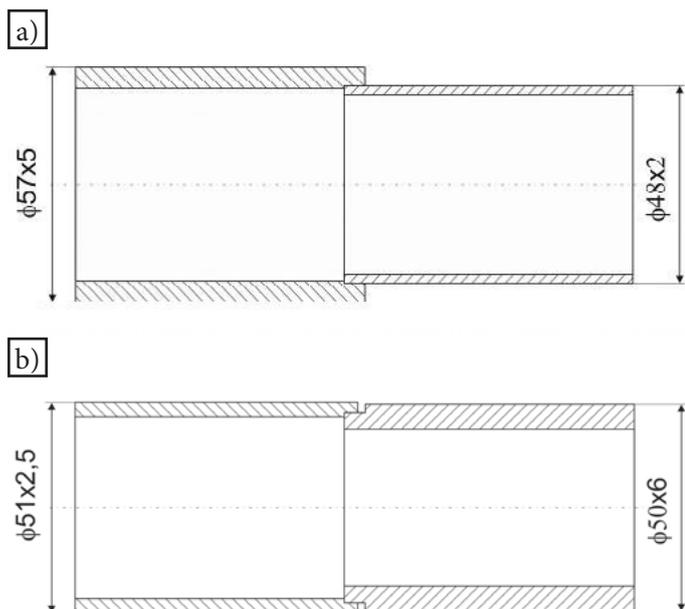


Fig. 2. Schematic diagrams of the joints representing the welded joints of the manifold unit: a) turbine-capsule joint, b) capsule-collector joint

### Joint of the turbine with the compensating capsule

The interface between the elements of the turbine and the compensating capsule were initially designed for arc welding and the fillet weld. The laser welding of the above-named joint enables the appropriate positioning of the laser head and the formation of the quasi-fillet weld. The term of the “quasi-fillet weld” signifies the situation where the joint is prepared as for the making of the fillet weld but where the transfer of stresses is not affected by the height of the isosceles triangle inscribed into the weld but only by the length of the molten area of the interface of the elements being joined ( $s$ ) (Fig. 3a). In accordance with the PN-EN ISO 16514:2005 standard concerning

the laser welding procedure classification, the above-named weld in the overlap joint or T-joint is referred to as the “fillet weld” (incomplete penetration)”.

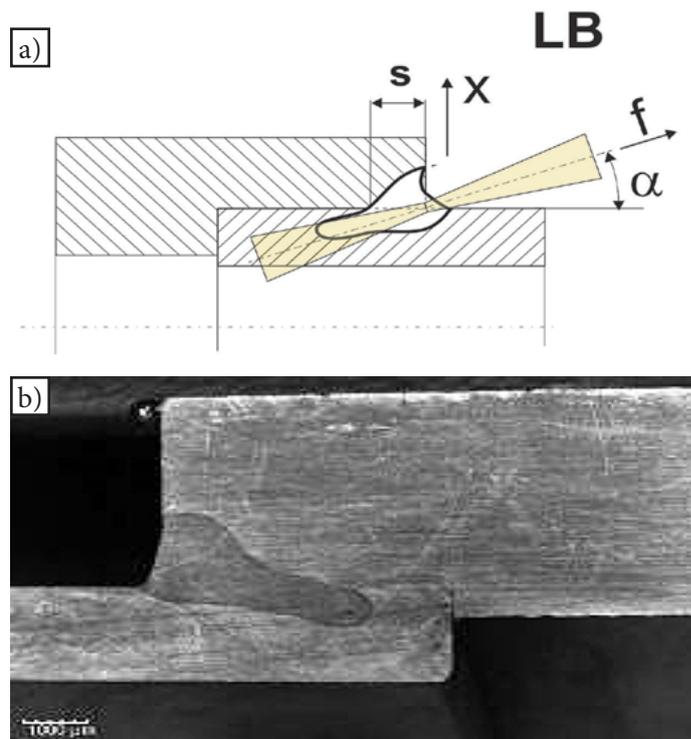


Fig. 3. Schematic diagram of the measurement of the penetration depth in the laser welded turbine-compensating capsule joint (a) and the exemplary macrostructure of the laser welded joint (b):  $\alpha$  – angle of the inclination of the laser beam propagation direction,  $f$  – position of the laser beam focus along the axis of the laser beam propagation (laser beam defocusing degree),  $x$  – shift of the laser beam focus towards the visible edge of the interface of the elements being joined in the direction perpendicular to the axis of symmetry of the turbine and compensating capsule

The initial welding tests enabled the identification of the initial parameters of the laser welding process (Table 1), hereinafter referred to as reference parameters. The laser welding process was stable. Visual and penetrant tests did not reveal the presence of surface welding imperfections or the weld discontinuity resulting from the improper positioning of the laser beam (Fig. 4a–b). The welded joint was cut in the axis of the tube cross-section. As a result, two metallographic specimens of opposite areas were obtained. Macroscopic tests did not reveal the presence of internal imperfections. The tests involved measurements of the penetration depths of welds  $s_1$  and  $s_2$ , located on the opposite sides of the section (Table 1).

Table 1. Laser welding parameters and penetration depths obtained in the reference joint of the turbine with the compensating capsule

Specimen no.	Laser beam power P [W]	Welding rate v [m/min]	Angle $\alpha$ [o]	Defocusing f [mm]	Shift x [mm]	Penetration	
						s1 [mm]	s2 [mm]
4	2 500	1.5	20	0	0	2.98	2.89

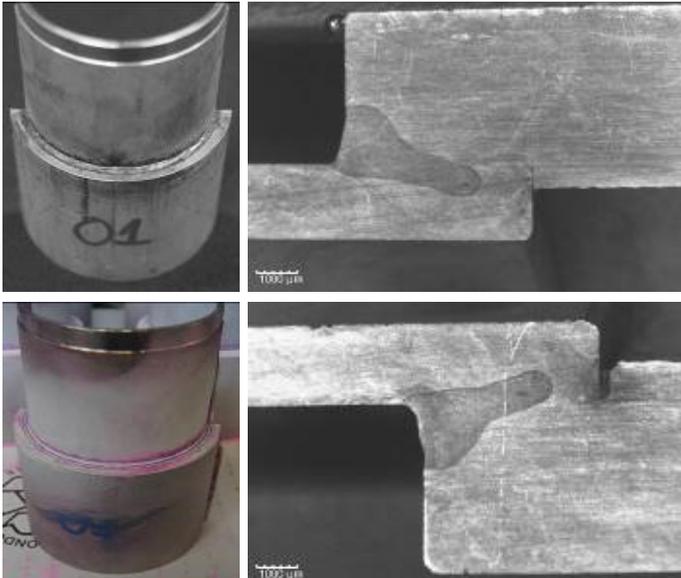


Fig. 4. Weld face (a and b) and weld macrostructure (c and d) in the laser welded joint of the turbine with the compensating capsule

Table 2. Laser welding parameters and penetration depths obtained in the joint of the turbine with the compensating capsule

No.	Spec. no.	Laser beam power P [W]	Welding rate v [m/min]	Angle $\alpha$ [o]	Defocusing f [mm]	Shift x [mm]	Penetration	
							s1 [mm]	s2 [mm]
1	4	1500	1.5	20	0	0	1.86	1.84
2	3	2000	1.5	20	0	0	2.29	2.16
3	1	2500	1.5	20	0	0	2.98	2.89
4	2	3000	1.5	20	0	0	2.95	2.31
5	5	2500	1	20	0	0	2.93	3.9
6	6	2500	2	20	0	0	2.55	2.16
7	7	2500	1.5	20	0	0.5	3.13	2.99
8	9	2500	1.5	20	0	1	0.00	0.00
9	10	2500	1.5	40	0	0	1.32	1.34
10	11	2500	1.5	40	30	0	1.48	1.17
11	12	3500	1.5	40	30	0	1.54	1.38
12	14	1500	1.5	70	0	0	0.60	0.62
13	16	2000	1.5	70	0	0	0.91	0.00
14	15	2000	0.82	70	20	0	0.57	0.72
15	17	2500	0.82	70	20	0	1.88	1.2
16	18	2500	0.66	70	30	0	0.93	0.94

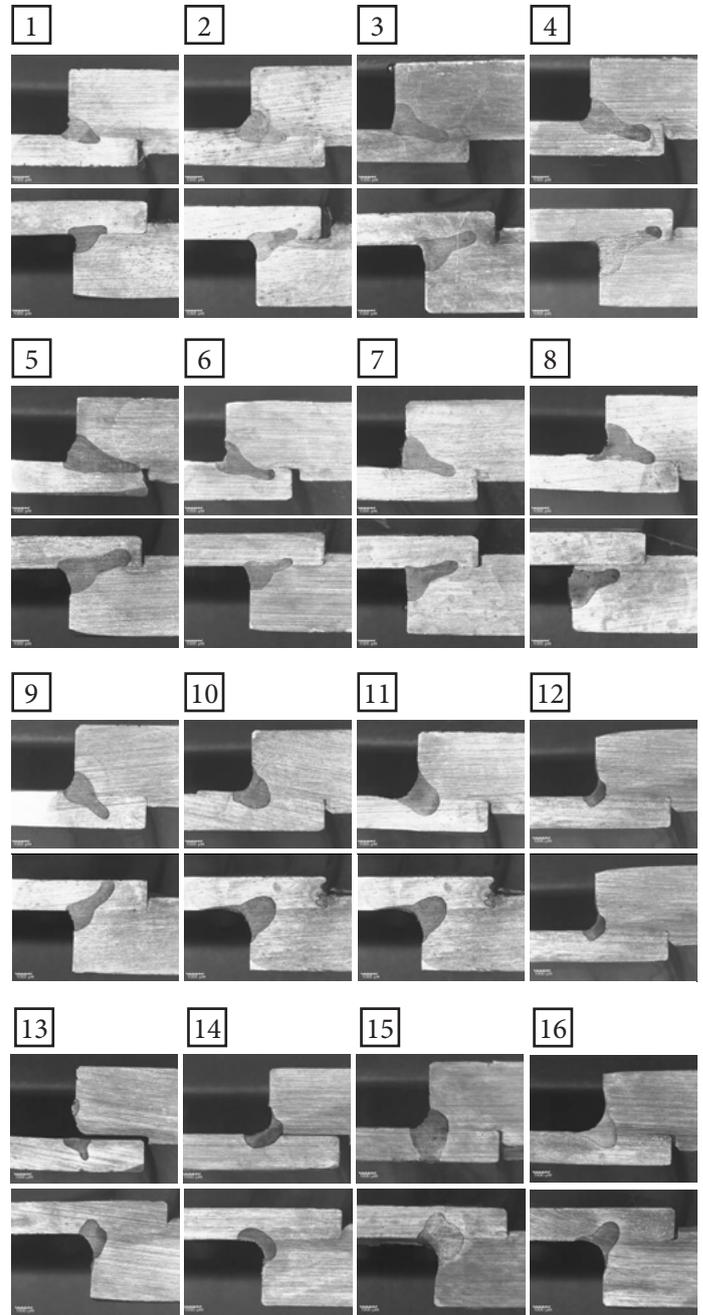


Fig. 5. Macrostructures of the laser welded joint of the turbine with the compensating capsule; parameters as in Table 1

The reference parameters were used in the tests of the laser welding of the turbine and the compensating capsule in relation to variously adjusted welding parameters (Table 2). Figure 5 presents the faces of the welds. Figure 6 presents the macrostructures of the welds (two macrostructures per joint).

The minimum adjustable angle of beam insertion into the interface area ( $\alpha = 20^\circ$ ), dependent on the laser beam caustic, enabled the obtainment of a weld characterised by a proper shape and penetration depth  $s$  dependent on the applied power of the laser beam and

a welding rate (Fig. 5 and 6, macrostructures 1 through 6). The maximum penetration depth, amounting to approximately 3 mm, was obtained in relation to laser beam power restricted within the range of 2500 W to 3000 W and a welding rate of 1.5 m/min (macrostructures 3 and 4, Fig. 5) as well as in relation to a laser beam power of 2500 W and a welding rate of 1 m/min (macrostructure no. 5, Fig. 5). An increase in laser beam power combined with constant welding rate  $v = 1.5$  m/min was accompanied by an increase in penetration depth  $s$  and an increase in the penetration depth in the laser beam propagation axis (Fig. 5, macrostructures 1–4; Fig. 6, Table 2). In relation to a beam power of only 1500 W, penetration depth  $s$  was similar to the capsule wall thickness amounting to 2 mm. The use of laser welding having a laser beam power of more than 2500 W (where the beam focus was located on the material being welded –  $f = 0$  mm) did not significantly affect penetration depth  $s$ , but only led to greater penetration into the capsule material along the laser beam propagation axis. The foregoing resulted from the applied laser beam insertion angle and the limited increase in the laser weld width along with the increase in the beam power. Hence, in relation to  $\alpha = 20^\circ$ ,  $f = 0$  mm,  $x = 0$  mm and  $v = 1.5$  m/min, the adjustment of laser beam power restricted within the range of 1500 W to 2000 W seems sufficient. The obtained differences in penetration depth in two opposite areas (where metallographic specimens were made) were nearly insignificant; only in relation to a power of 3000 W the difference amounted to 0.97 mm. The foregoing resulted from the specific shape of the laser weld (narrow lower part of penetration), the applied angle of beam insertion into the interface area and the accuracy with which the elements to be welded had been made. In spite of obtaining similar penetration depth along the beam propagation axis, slight changes in the head position or unprecise workmanship resulted in a situation where, in one of the cross-sections,

the fusion area “missed” the interface of the elements being welded (along a similar length). A similar effect could be observed in relation to the minimum test welding rate (Fig. 7).

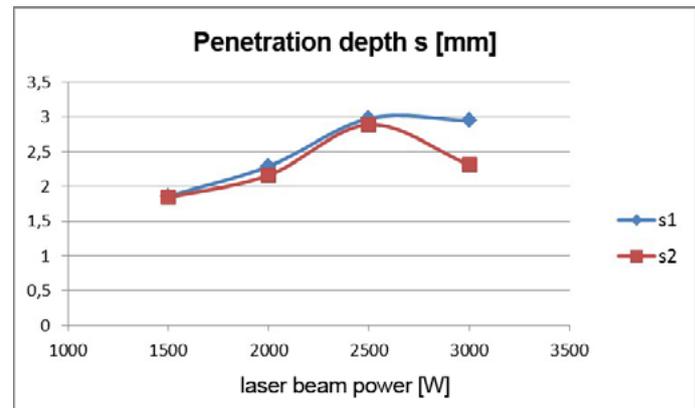


Fig. 6. Effect of the laser beam power on the penetration depth in the laser welded joint of the turbine and the compensating capsule ( $v = 1.5$  m/min,  $\alpha = 20^\circ$ ,  $f = 0$  mm,  $x = 0$  mm)

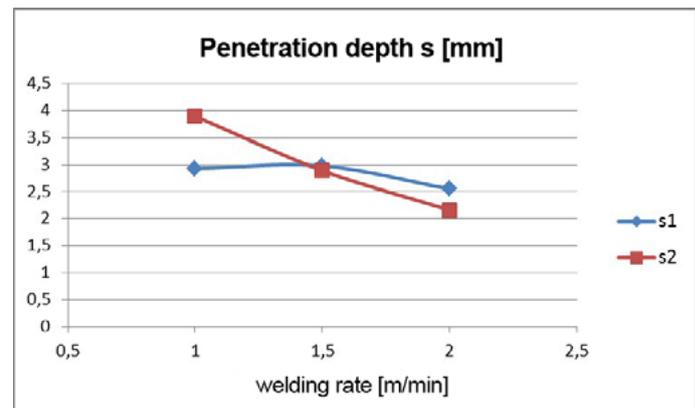


Fig. 7. Effect of the welding rate on the on the penetration depth in the laser welded joint of the turbine and the compensating capsule ( $P = 2.5$  kW,  $\alpha = 20^\circ$ ,  $f = 0$  mm,  $x = 0$  mm)

Difficulty obtaining high dimensional tolerance in cast elements and the fact that the tolerance of detail workmanship might overlap with the tolerance of the device positioning the laser head necessitated the investigation concerning the effect of shift  $x$  (Fig. 3) on the size of penetration  $s$  in the welded joint (Fig. 8). It was observed that an increase in shift  $x$  above 0.5 mm increased the risk related to the lack of penetration (Fig. 6, macrostructure 8). In relation to shift  $x = 1$  mm, in one area of the cross-sectional plane, the laser beam did not melt the interface of the elements. The aforesaid imperfection was easy to notice during the visual or penetrant tests of the joint. In the second area,

the laser beam partially melted the interface of the elements in the weld face and root area, yet left central area of the interface unmolten (Fig. 9). The aforementioned imperfection was very important particularly in terms of mechanical properties and, at the same time, impossible to detect in visual tests or leak tests.

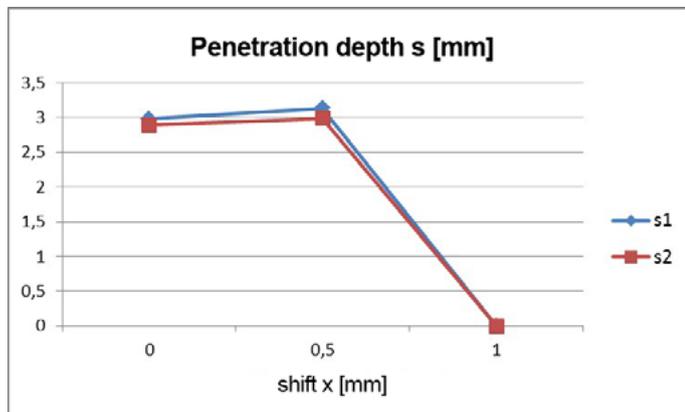


Fig. 8. Effect of shift x (Fig. 3) on the penetration depth in the laser welded joint of the turbine and the compensating capsule ( $P = 2.5 \text{ kW}$ ,  $v = 1.5 \text{ m/min}$ ,  $\alpha = 20^\circ$ ,  $f = 0 \text{ mm}$ )

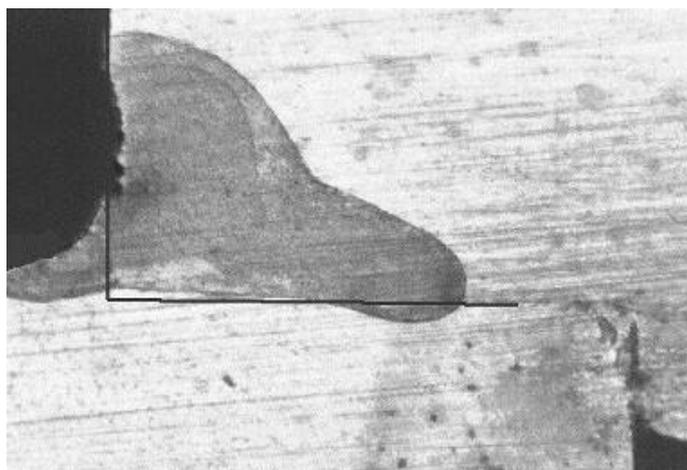


Fig. 9. Macrostructure of the laser welded joint of the turbine and the compensating capsule; shift  $x = 1 \text{ mm}$ ; the marked profile of the turbine edge and the visible lack of penetration

Because of the shortest possible distance between the laser beam propagation axis and the interface of elements being welded, the angle used in the aforesaid tests, i.e.  $\alpha = 20^\circ$ , was an optimum one. However, because of the design of the final element of the capsule and the turbine and the fixtures attaching and positioning elements to be welded, the above-named angle could be unobtainable. As a result, related welding tests involved the use of the angle of laser beam insertion into the interface greater than

the initial one. The welding tests involving the use of an insertion angle of  $40^\circ$  ( $\alpha$ ) resulted in shallower penetration depth  $s$  as well as in the increased risk of melting the capsule wall through and through (Fig. 5, macrostructure 9). Subsequent tests performed at greater angle  $\alpha$  involved the lower power of the laser beam and/or the defocused beam.

The defocusing of the laser beam, i.e. the lifting of the laser head by  $f = 30 \text{ mm}$ , at beam insertion angle  $\alpha = 40^\circ$  led to a change in the shape of the weld. The welding tests were performed in relation to a laser beam power of  $2500 \text{ W}$  (Fig. 5, macrostructure 10) and  $3500 \text{ W}$  (Fig. 5, macrostructure 11). The shape of the welds obtained in this manner was similar to that of arc welds, i.e. characterised by the wider face of the weld and by shallower penetration, the value of which was similar to that of the weld width. The face of the obtained weld was characterised by very high aesthetics, which indicates the transition (as a result of laser beam defocusing) from the keyhole welding to the melt-in welding process. Although the metallographic specimen of the joint welded using a power of  $3500 \text{ W}$  did not reveal the melt-through of the capsule wall, the visual inspection of the capsule interior revealed local penetration in the overlap area, i.e. the area of a cumulated heat input to the joint.

The laser welding tests performed at laser beam insertion angle  $\alpha = 70^\circ$  and with the laser beam focus located at the interface of the materials being welded revealed a significant difficulty providing the stability of the welding process. The laser beam slid along the edge of the turbine inlet. On one side of the girth welded joint, the laser beam was partly reflected against the turbine inlet edge and, as a result, got defocused creating a wide weld. On the other side of the joint (where a gap was present) the laser beam partly melted the edge of the turbine inlet and penetrated the capsule material (Fig. 5, macrostructure 13). The defocusing of the laser beam by  $f = 20 \text{ mm}$  combined with the reduction of the welding rate enabled

the obtainment of a wider weld characterised by the aesthetic face (Fig. 5, macrostructure 14). However, penetration depth  $s$  decreased to approximately 0.6 mm. The increase in the laser beam power increased penetration depth  $s$ , yet, because of laser beam insertion angle  $\alpha = 70^\circ$ , penetration into the capsule was deeper as well, which, consequently, could lead to the local melt-through. (Fig. 5, macrostructure 15). The further defocusing of the laser beam to  $f = 30$  mm accompanied by the reduction of the welding rate to 0.66 m/min provided the stability of the welding process. The capsule wall was not melted through and through; penetration depth  $s$  amounted to approximately 1 mm (Fig. 5, macrostructure 16).

## 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, 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). Activities aimed at improving the stability and repeatability of the laser welding process 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 turbine housing as well as the narrowing down of tolerances related to the workmanship of such

elements (aimed at their better match) may significantly increase the price 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 by the complex shape of such elements.

The tests of the laser welding of the turbine and the compensating capsule revealed that the most favourable position of the laser head required the application of the smallest possible angle  $\alpha$  so that the direction of laser beam propagation could be as close to the interface of the elements subjected to welding as possible (parameters no. 3 in Table 2). The performance of the laser welding process at a greater angle (e.g. related to/restricted by laser head positioning) required the defocusing of the laser beam, consequently increasing the weld volume and improving the stability of the welding process (parameters no. 16 in Table 2).

The above-presented results constitute the outcome of 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 (IN-NOMOTO) 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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