Experimental studies on the possibility of using a pulsed laser for spot welding of thin metallic foils

Abstract: The purpose of the experiment was to study the influence of the laser beam in pulse mode on metallic foils in order to obtain a spot weld. The welding process was carried out using the overlap weld method, using spot welds in various quantities. The Nd - YAG BLS 720 pulsed laser was used to conduct the experiment. The impact of the number of spot welds on the value of force needed to break the sample was examined. A number of measurements were carried out to determine the best process parameters. Butt welding and overlap welding were also performed using a continuous weld consisting of spot welds. Weld strength tests were performed to select the most appropriate parameters for the process under consideration.

Keywords: pulse laser, laser spot welding

1 Introduction

Laser welding is one of the main applications of lasers in the technological treatment of materials. Due to the characteristics of the process: small amount of heat input to the material, universality of the process, precision and ease of automation, laser welding is a technology competitive to the common technologies. It allows to obtain a weld of the highest quality without the need to use additional hot-melt materials. The range of materials that can be joined using the laser method is very broad, covering most metals and their alloys, as well as plastics. Laser welding allows for making various types of joints in any position. The parameters of modern lasers allow for effective and highly efficient joining of large-size elements as well as micromachining of elements with thicknesses in the micro range. Due to its efficiency and precision, laser welding becomes a competitive method both for arc welding in gas shields and pressure welding, as well as for modern methods of electron beam and plasma arc welding. In many cases, it can also be a supplementary method to these welding methods [1–3].

Due to their many advantages, laser technologies are used for cutting, welding, marking, surface hardening, flood welding, remelting and micromachining. The energy range of a pulsed laser determines its ability to produce a pulse of a specified power, pulse repetition rate and duration. The weld formed as a result of the impact of the laser beam emitted in the impulse mode consists of many overlapping spot welds. The range of overlapping of individual pulses, determined in percent, shows to what extent the material area melted by a single pulse overlaps with the area created by the preceding pulse. With parameters such as welding speeds and pulse repetition rates, the tightness of the weld, the amount of heat supplied to the weld metal and the actual melt depth can be optimised, and the homogeneity of the weld structure can be affected. Pulse mode lasers are particularly suitable for welding thin-walled elements that are not resistant to large amounts of heat supplied to the joint, causing cracks or deformations [15–17].

Laser micro-welding is a well-established joining process in the development of microsystems. In particular, the emitted laser energy is absorbed and stored by the workpiece. The portion of energy that heats and melts the material is the actual welding energy. During heating, the energy is dissipated by heat conduction losses. This causes thermal induction and deformation in the welded material. If the thickness of the elements to be joined is small, the relative deformation increases exponentially. The ratio of gap width to material depth has a major impact on the quality of the joint. The larger the gap and the smaller the thickness of the material, the more difficult it is to make a joint [4–6].

The process of laser micro-welding has found a wider application with the growing trend of miniature components and devices in the electronics, medical, photonics and precision industries. These applications require a fast, precisely controlled and individually adjustable power supply to the welding area [11, 12]. The unique ability of the laser beam to focus on a very small size and produce a fast
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but minimal heat transfer makes it the right tool for micro-welding. Laser intensity is scalable in a wide range of ways, both locally and temporally. Laser welding has become the most suitable and preferred method for the automated production of miniature high-value devices compared to conventional resistance welding and brazing [7, 8]. The micro-welding process requires great precision in terms of the selection of treatment parameters and the tooling used. Errors at the stage of planning lead to inconsistencies in the weld obtained. In the case of welding of different types of materials, defects resulting from different physical properties may occur [13, 14]. Laser micro-welding allows to avoid deformations of welded parts, thus maintaining narrow tolerances and minimal interference with the surrounding parts, and is therefore used to join thin metallic foils with a thickness of 0.025 – 0.125 mm and small tubular parts. When microcircuits are joined, the gap distance between the parts to be connected must be less than 5% of their thickness. In some cases, close contact between parts is essential to produce a precise and durable joint. As a rule, the micro-welding process is carried out in an atmosphere of shielding gases, protecting the material from the reaction between the welded material and components of air. The resulting welds are characterized by low volume and high durability [9, 10].

Spot welding is required to fix parts in a certain position before welding the seam. A strong weld is achievable when the welding puddle is deeper than the thickness of the thinner element. The right geometry of the element, precision machining, correct tooling and clamping as well as optimal process parameters are necessary to create a weld that is resistant to cracks, porosity and deformation. The materials often used for laser micro-welding are copper, aluminium, nickel, steel, gold, platinum and titanium alloys [11, 12].

Laser micro-welding is a fast and repeatable process that offers many benefits including:

- High quality welding (e.g. smooth seam surface, no oxidation, no deformations),
- There is no need for additional fluxing agents,
- A minimal heat affected zone, minimising damage to the workpiece,
- It is a non-contact process with very good access to hard-to-reach welding areas,
- There is no need for a vacuum chamber as required by electron beam welding,
- High speed of the process,
- This technique can be used to join elements with different geometries and thicknesses.

The disadvantages of the micro-welding process include the need to prepare the workpieces thoroughly before treatment. The limitations on the thickness of the welded material, excessive deformation, difficulty in achieving close contact between the pairs of elements to be joined.

2 Experiment

The process of micro-welding thin metallic foils was carried out with the use of the Nd – YAG BLS 720 lasers with the following parameters: maximum energy per pulse 400 J, maximum power 150 W, operating frequency 0.1 – 500 Hz, pulse length 0.1 – 20 ms, spot diameter 0.6 mm, wavelength 1064 nm. The materials used in the experiment were 0H18N9 steel foils with a nominal thickness of 50 µm and Ni 99.9% nickel foil with a nominal thickness of 100 µm. A series of measurements were taken to verify the actual thickness of the foil and the deviation of the actual thickness from the nominal thickness was found to be within 1 µm. The biggest problem was the positioning of the elements in relation to each other due to their small thickness. Special tooling was used for this purpose. Spot welds have been made in various quantities at a distance of 1mm. The micro-welding process was carried out in the atmosphere of a protective gas – argon. A schematic diagram of the experiment is shown in Figure 1 and Figure 2 shows the geometric profile of the test weld face.

![Figure 1: Diagram of the test station, where: 1 – laser head, 2 – laser beam, 3 – focusing lens set, 4 – focused laser radiation, 5 – welded material.](image-url)
Visual analysis of spot welds made at different pulse lengths was performed using the Hirox KH-8700 optical microscope. During the initial attempts to weld the foil, the laser parameters were selected in such a way as to obtain full weld penetration of the upper and lower elements in the overlap joint of the welded foils. The oscillated parameter was the pulse duration. On the basis of visual tests, optimal parameters of the micro-welding process have been determined for specific materials.

During the initial attempts to weld the foil, the laser parameters were selected in such a way as to obtain full weld penetration of the upper and lower elements in the overlap joint of the welded foils. The oscillated parameter was the pulse duration for the constant energy of 90J in the pulse. On the basis of visual tests, optimal parameters of the micro-welding process have been determined for specific materials. In the case of the 0H18N9 steel foil, the best quality of the spot weld was obtained with a pulse duration of 1ms (Figure 4). In the case of a shorter pulse duration, the exact weld penetration of the lower element in the joint was not obtained. For a pulse duration of 1.5 ms, the upper element was burnt out. Further increase of this parameter resulted in complete burnout of the welded foils. For the nickel foil the optimum pulse duration was equal (Figure 4). With a shorter pulse duration, an accurate and good quality weld was not achieved. Increase in the pulse duration caused an increase in the heat affected zone around the weld obtained. When selecting optimal parameters for joining nickel foil with 0H18N9 steel foil, the biggest problem was to obtain a good quality joint penetration of both elements due to different thickness of the materials being joined. The best quality of the spot weld was obtained at the duration of the pulse equal to 4ms (Figure 5). Increasing this parameter resulted in complete burnout of the welded foils.

After determining the correct welding parameters for each material, the foil joints were made using different amounts of spot welds to test the strength of the joints. The welds were made at a distance of 1mm. The weld strength test was performed on an Instron 4502 universal testing machine. The strength test specimens were cut using the Trumpf TruMICRO 5325c laser in cold ablation technology.
Figure 4: Selection of welding parameters for nickel foil. View of the weld root for the following pulse lengths (from left to right): 8ms, 7ms, 6ms and 5ms.

Figure 5: Selection of welding parameters for joining nickel foil and 0H18N9 steel foil. Face view for the following pulse lengths (from left to right): 7ms, 6ms, 5ms, 4ms, 3ms and 2ms.
to eliminate heat impact on the material while maintaining defined, repeatable dimensions – when the sample was overlapped, a tensile test sample of standard dimensions was obtained. The tensile test process was carried out at a very low velocity of 0.1 mm/s due to the small thicknesses of the materials tested. Two, three and four-spot welds were considered.

Table 1: Summary of the forces needed to break the prepared samples.

| Type of weld  | 0H18N9/0H18N9 | Ni/Ni | 0H18N9/Ni |
|--------------|----------------|-------|-----------|
| two-spot     | 37.8           | 128   | 122       |
| three-spot   | 43.2           | 177   | 137       |
| four-spot    | 47             | 226   | 156.1     |

For the overlap joint of 0H18N9 steel foil, the value of the breaking force increases slightly with an increase in the number of spot welds, but in each case the breakage occurred in the area of the base material and the weld remained intact. In the case of nickel foils, the breakage occurred in the weld area. In the case of a dissimilar joint, the value of the breaking strength is much higher than for steel itself and slightly lower than for a clean nickel foil joint. With the increase in the number of spot welds, the breaking force in this case increased by about 15 N. In the case of the 0H18N9/Ni joint, the rupture occurred in the base material area, and the weld remained intact.

An attempt was made to obtain a continuous weld consisting of spot welds in butt and overlap welding. The butt welding was carried out on 0H18N9 steel foil with a thickness of 50 µm, while the overlap welding was carried out on 0H18N9 steel foil and a dissimilar joint of 0H18N9 steel foil with nickel foil with a thickness of 100 µm, with previously determined optimal process parameters. Due to the significant difference in the thickness of the elements, it was not possible to carry out butt welding of dissimilar materials. The process of butt welding of 0H18N9 steel foil was carried out with a pulse duration of 1 ms, a pulse rate of...
10 Hz and a welding speed of 200 mm/min. The wide heat affected zone created by welding was apparent here, as a result of which the base material around the weld was deformed. For joining the nickel foil with 0H18N9 steel foil, the pulse duration was increased to 4ms. The resulting weld does not maintain a uniform geometry along the entire length of the joint (Figure 7). The best results were obtained for the overlap joint of 0H18N9 (Figure 7 and 8) steel foil with the same process parameters as for butt welding. The weld retains the same geometry along the entire length of the joint, and the resulting heat affected zone is small and does not affect the geometry of the base material around the weld.

Figure 8: Isometric view of the 0H18N9/0H18N9 weld surface 3D profile tested on the Talysurf CCI Lite optical profiler.

3 Conclusions

The aim of the study was to analyse the possibility of using a pulsed laser for welding thin metallic foils. The tests were carried out using the Nd – YAG BLS 720 laser. The material used in the study was 0H18N9 steel foil with a thickness of 50 µm and Ni 99.9% nickel foil with a thickness of 100 µm. The micro-welding process was carried out using the overlap weld method. A number of test welds have been carried out to determine the optimum process parameters. In the case of the 0H18N9 steel foil, the best quality of the spot weld was obtained with a pulse duration of 1ms. For nickel foil it was 5 ms. For a dissimilar joint, the best quality of a spot weld was obtained with a pulse duration of 4 ms. The foil was then joined using different amounts of spot welds to test the strength of the joints. The spot welds were made at a distance of 1 mm. On the basis of the analysis of the diagrams obtained, the force required to break the sample was determined for different number of welds and individual materials. In case of the overlap joint of 0H18N9 steel foil, the value of the breaking force increases slightly with an increase in the number of spot welds. If the joint is dissimilar, the breaking load increases by approx. 15 N as the number of spot welds increases. The highest strength of the welds was obtained for the overlap joint of the nickel foil. Along with an increase in the number of welds, an increase of about 50 N in the force required to break the sample was noted. An attempt was made to obtain a continuous weld consisting of overlapping spot welds in butt and overlap welding. The butt welding process was carried out on a 50 µm thick 0H18N9 steel foil. The biggest problem was the positioning of the joined elements. Due to the low foil thickness – 50 µm – the heat supplied to the base material during the welding process led to a deformation of the base material around the weld. In the case of the overlap joint of nickel foil and 0H18N9 steel foil, a weld was obtained that does not maintain a uniform geometry along the entire length of the weld. In order to achieve a homogeneous weld, the material had to be cooled down every time the laser beam pulse interacted with the material. The best results were obtained for the overlap joint of 0H18N9 steel foil with the same process parameters as for butt welding. The weld maintains a uniform geometry along the entire length of the weld, and the resulting heat affected zone is small and does not affect the geometry of the base material around the weld.

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