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Laser Welding of Metal-Polymer-Metal Sandwich Panels

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Abstract: In the production of metal-polymer multilayer composite parts, e.g., for automotive applications, the possibilities of thermal joining are limited due to the instability of the polymer core at elevated temperatures. Accordingly, such materials require a special approach to their welding. The three-layered metal-polymer-metal samples were made of DPK 30/50+ZE dual-phase steel as cover sheets that were electrolytic galvanized, and a polypropylene-polyethylene foil as core material, with thicknesses of 0.48/0.3/0.48 mm. The samples were welded on both sides using a 1.06 µm Nd:YAG ROFIN StarWeld Manual Performance laser. Significant improvements of the welding conditions are achieved by machining the edges of materials to be welded. The parameters of laser welding were chosen in such a way that the polymer structure remained almost unchanged. The weld thickness was about 40% of the thickness of each steel layer. It was established that within the selected laser processing parameters the melting occurred uniformly, while the polymer layer practically did not change its structure. Therefore, it can be stated that two-sided joint welding of metal-polymer-metal composite sandwich panels, without significant degradation of the polymer core layer, is feasible.

Keywords: laser welding; sandwich panel; metal-polymer-metal; three-layer material; steel; polymer core layer

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1. Introduction

Sandwich panels are promising composite materials, which combine advantages of the used mono-materials. For this reason, these possess improved properties that each mono-material alone would not deliver, such as low density, high bending resistance, energy absorption, high load carrying capacity in combination with a low specific weight [1–3]. Separately, metal-polymer-metal multilayer composite systems (MPM) can compete with conventional sheet materials in the construction, naval, automotive and aerospace industries [4,5]. The lower weight of sandwich panels compared to mono-metallic sheets leads to fuel savings in automotive and aerospace equipment. This contributes towards achieving economic and ecological objectives. Moreover, they also ensure the damping of vibrations, as well as with their low thermal conductivity due to the polymer material between the metal layers, thermal insulation effects. By combining these materials with reinforcing elements while designing different components, it is possible to compensate for the lack of rigidity and strength of the sandwich panels [6,7].

In the production of polymer-based multilayer composite parts, e.g., for automotive applications, the possibilities of thermal joining are limited due to the instability of the polymer core at elevated temperatures. When processed at higher temperatures, the polymer can evaporate and even corrode the metal [8,9]. Therefore, such materials require a special approach to their welding. One way to overcome this problem is by improving existing and applying new technologies, such as power beam welding techniques, which are used to manufacture parts and assemblies for various machines and systems in a cost-effective way. Sufficiently broad technological possibilities are determined by the following properties of the power beam: flexible control of energy and time characteristics, and possibility of parameters optimization in a wide range.

Laser welding is a progressive non-contact technological process. It offers the possibility to process hard-accessible or local areas of parts in the absence of vibrations and other negative influences on the material. Compared to conventional metal joining methods, laser welding is a more attractive processing method due to the high processing speed and the high accuracy of the energy input [10,11]. This welding method ensures the possibility to reduce the heat affected zone and to avoid the appearance of defects. The physical processes occurring in the heat affected zone are localized in depth and area. The original material properties are retained in the remaining volume and there is no significant deformation in the parts undergoing laser treatment. These are very important factors during the processing of MPM systems.

The advantages of a laser heating source for welding of thin metals, using the mechanism of thermal conduction, are related to the fact that due to the absence of mechanical impact on the melt pool, burns and undercuts, even in local areas of the trajectory, may be excluded [12,13]. This is primarily determined by the fact that the laser beam exerts no pressure on the surface of the melt, whereas, for example, the electric arc possesses considerable pressure, several orders of magnitude higher than the pressure during laser melting [14]. Laser welding should be recommended when it is necessary to obtain a high precision construction, for which the shape and dimensions should not change much after welding. The preferred joint is the butt joint [15]. Lap and butt joints generally have high sensitivity to stress concentrators.

The polymer core of the composite material tends to break down under high temperature exposure and its properties can considerably deteriorate. Therefore, investigations on the subject of forming a strong welded joint by locally welding the metal layers to each other without considerable degradation of the polymer layer are necessary [16,17]. Two different types of laser welding of multilayer material are presented in [18,19]—one-sided and two-sided welding. It is stated that the two-sided welding, which involves the welding of the sheet material on both sides, can be used to reduce the impact of the process on the core and result in the absence of evaporation of the viscoelastic core. The main problem is controlling the welding depth by correctly selecting the process parameters without raising the core temperature above the melting temperature. However, studies have only been performed for a one-sided welding [19]. During such processing, the polymer core begins to deteriorate in the processing zone due to excessive heating, which leads to a degradation of the damping characteristics of multilayer composites. The sandwich material comprised two 0.55 mm steel sheets of IF260 separated by a viscoelastic polymer core 45 μm thick; the outer surfaces of the steel blanks were coated with HDG+Z140. Considering the results of these studies, it was reported in [20] that the laser welding used to join metallic materials cannot be applied to sandwich materials without degradation of the central polymer layer. According to [21], pulsed laser welding was applied to obtain a butt joint of a steel polypropylene material. Degradation of the polymer core was avoided, but only the upper sheet was joined. Pulsed laser welding was also applied to an aluminum-polypropylene multilayer material. However, after joining, such weld defects as central cracking, porosity, and undercut were observed [22]. Cracks were observed in the joint due to the high cooling rate that was maintained to prevent degradation of the polymer layer. Nevertheless, it has been noted that the elimination of cracks, as well as an increase in the thickness of the welded sandwich materials, are possible. More studies are needed for this, and the research in this area looks promising.

As with most other sheet materials, MPM triple-layer sandwich materials are cut into strips or blanks to the required dimensions for further processing. Strip cutting is a preparatory operation that is carried out with various types of shears, such as guillotine, circular, lever or vibratory shears [23]. During the cutting process, the sheet material passes through three successive stages: elastic, plastic and shearing [24]. As a result, the quality of the cut edges may not meet the requirements of the subsequent laser welding process. The presence of even a minimal gap between the edges to be welded is a challenge and can introduce defects in the geometry of the weld and leave a window for direct irradiation on the polymer core. Alignment of the edges of the materials to be welded can contribute to the minimization of the gap during their joining [25].

The appropriate regimes for laser welding of steels provide a combination of such parameters as qualitative weld formation, sufficient operating strength, and acceptable mechanical properties of the welded joint. The quality and reliability of laser-beam welded joints is largely determined by the accuracy of the assembly of the elements to be welded. This type of assembly must ensure the possibility for tight fitting of the edges along the entire length of the weld with a minimum gap and edge misalignment. The offset height of one edge in relation to the other must not exceed a certain value from the thickness of the parts to be welded. The necessary precision of the assembly is achieved by machining the edges to be welded [26,27]. When assembling for welding, tack welds are not recommended. If necessary, tack welds should be also executed by laser irradiation.

The purpose of this study is to investigate the possibility of the laser welding of metal-polymer-metal sandwich composites without significant degradation of the polymer core layer.

2. Experimental Investigations

To perform the welding on both sides, the three-layered MPM samples were made of DPK 30/50+ZE dual-phase steel (HCT500X, Thyssenkrupp Steel Europe AG, Duisburg, Germany, grade number: 1.0939, DIN EN 10346:2009-07 [28]) as cover sheets that were electrolytic galvanized and a polypropylene-polyethylene (PP-PE)—foil as core material [29,30] with thicknesses of 0.48/0.3/0.48 mm. A VEGA\\SB, Tescan scanning electron microscope (Tescan, a.s., Brno, Czech Republic) having a tungsten cathode with thermionic emission and a voltage range of 0.2–30 kV was used to examine the weld joint obtained by pulsed-periodic laser irradiation. Figure 1 shows a schematic diagram of the laser welding principle and the cross-sectional drawing with marked materials.

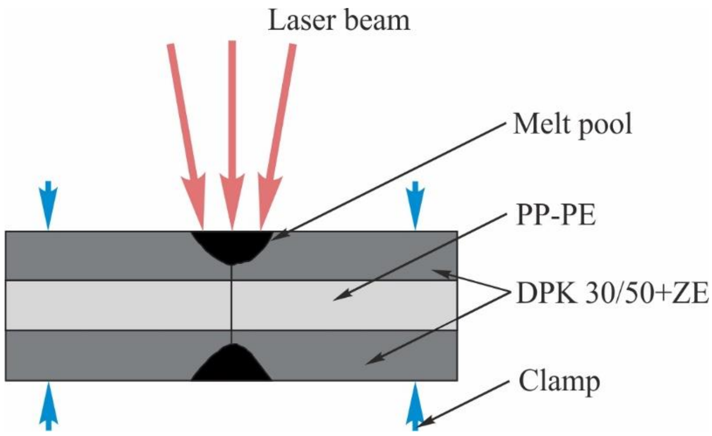


Figure 1. A schematic diagram of the laser welding principle.

Figure 2 shows the initial condition of the sample layers in the cross-section: the thickness of the edge of the upper metal layer is smaller than that of the lower layer. The edge of the polymer material is uneven after the cut. The middle part of the polymer edge extends and tears slightly during the cutting process. This protruding material appears as a bright irregular line between the upper and lower dark gray areas. During imaging with secondary electrons, the contrast is dominated by the so-called edge effect: more secondary electrons can leave the sample through the edges in comparison with the transition through the flat areas. This leads to an increased brightness in these areas [31,32]. On the slice of the lower layer, only a zone of plastic deformation is observed. On the slice of the upper layer of the material shown in Figure 3, the area corresponding to plastic deformation (below) and the shear zone (above) are clearly identified. In addition, on the slice of the upper layer there are noticeable fractures, which are formed when the material is being cut by scissors.

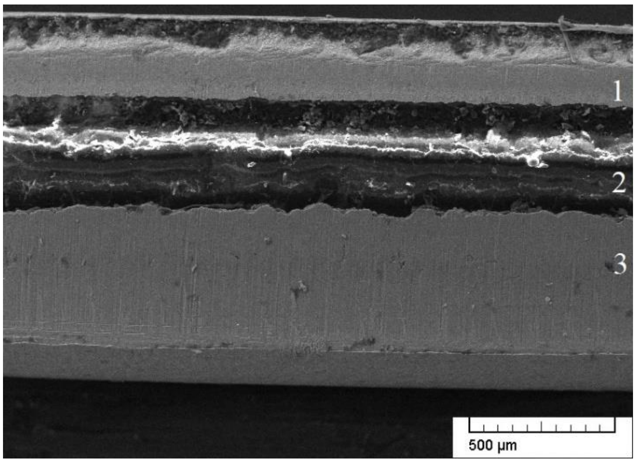


Figure 2. Initial layers of the sample in the cross-section when the material was cut by scissors: (**1**,**3**) DPK 30/50+ZE steel; (**2**) PP-PE foil.

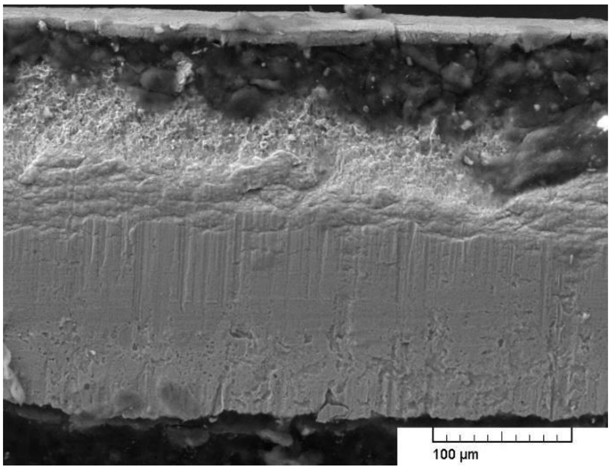


Figure 3. Image of the upper layer slice.

The MPM samples were welded using a 1.06 µm Nd:YAG ROFIN StarWeld Manual Performance laser (Rofin-Baasel Lasertech GmbH & Co. KG, Headquarters Laser Micro, Gilching, Germany). The main technical characteristics of the ROFIN StarWeld laser were as follows: maximum average power of the laser beam per pulse 50 W; maximum energy per pulse 100 J; pulse duration 0.5–50 ms; pulse frequency 0.5–50 Hz. The pulse configuration of the laser was chosen with an increased pulse leading edge. Satisfactory results were achieved by laser welding with a pulse energy of 5 J at a pulse duration of 3.5 ms and a pulse frequency of 4.8 Hz. The laser spot size on the material surface was 0.35 mm. The focal plane was positioned on the blank surface, the optical system had a focal length of 7.5 inches. During the welding, the processing depth amounted more than 40% of the thickness of the edges in the absence of deep cracks and without significant degradation of the polymer layer. The traverse speed of the laser spot was 250 mm/min. Figure 4 shows the top view of the welded joint of the upper metallic layer. On the surface in the vicinity of the melt pool, there are visible damaged areas of the zinc coating due to its high-temperature heating. The presence of zinc in the melt pool itself led to the formation of small surface cracks.

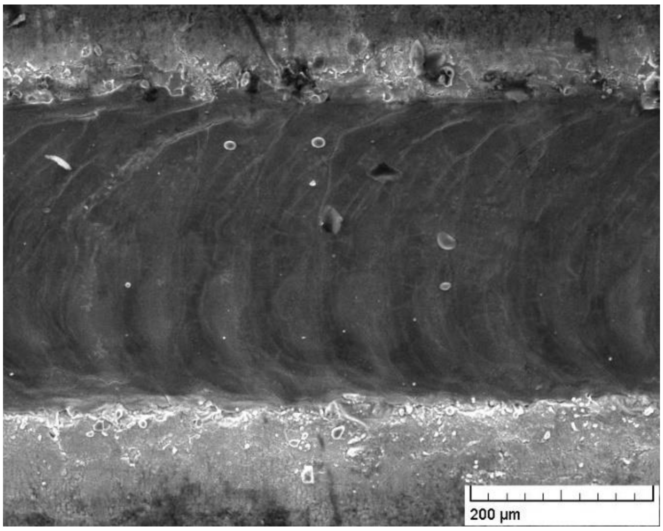


Figure 4. Top view of the welded joint.

The appropriate parameters were chosen, in such a way that the PP-PE structure remained almost unchanged. The three-layered MPM samples with a width of 25 mm were prepared for tensile testing of the welded joint. Tensile tests were performed on a Zwick Z50 kN Testing Machine (ZwickRoell GmbH & Co. KG, Ulm, Germany). The maximum tensile force was 0.8 kN, the maximum elongation was about 0.6 mm. A fractographic study of the fracture surface was performed to assess the quality of the welded joint (Figures 5 and 6). The fracture surface was studied at various magnifications with a scanning electron microscope, and it was established that its structure was homogeneous. The surface area of the fracture was characterized by fibrousness, absence of metallic luster, absence of defects in form of pores and nonmetallic inclusions. This fine-grained fibrous fracture without glossiness indicates a potentially sufficiently good ductility and high impact strength of the metallic material. An image of the fracture surface in the central part of the welded joint is shown in Figure 5. The steel and polymer layers of the sample are clearly visible. The weld thickness varied from 50 µm to 100 µm.

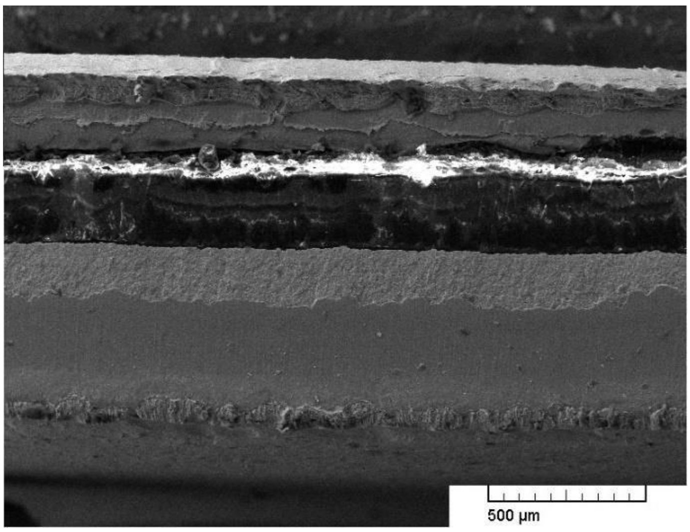


Figure 5. Surface of the fracture after laser welding.

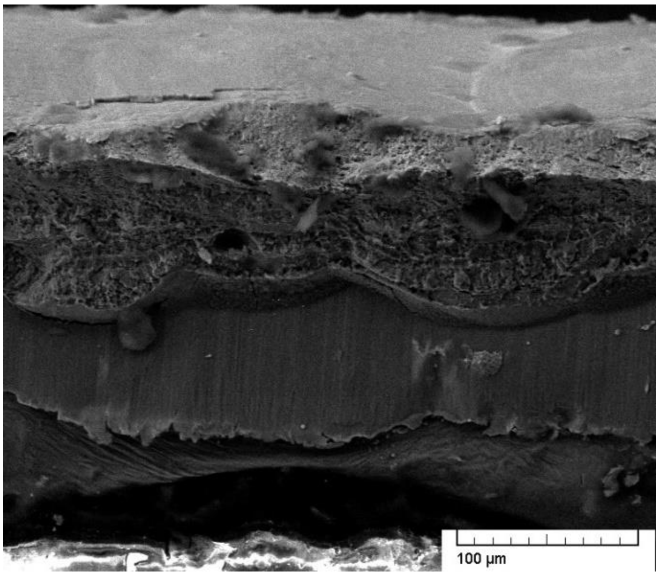


Figure 6. Sectional view of the surface of the fracture of the treated upper layer.

Therefore, it can be stated that two-sided joint welding of metal-polymer-metal composite sandwich panels, without significant degradation of the polymer core layer, is feasible. As this process of laser welding of sandwich panels is feasible, the question of improving the quality and strength of the welded joint arises.

Edge pre-treatment was carried out to improve the quality of the welded joint. The edges were machined by grinding and the zinc coating was removed from the near-joint area by mechanical grinding. Figure 7 illustrates the top view of the welded joint, created by welding the three-layered MPM samples alternately on both sides. The results for two-sided laser treatment were achieved using such laser welding parameters as the pulse energy of 8 J at a pulse duration of 5 ms and a pulse frequency of 2 Hz. The focal plane was positioned on the blank surface. The beam spot size on the material surface had also the value of 0.35 mm. The traverse speed of the laser spot was 100 mm/min. The weld thickness reached about 40% of the thickness of the each steel layer.

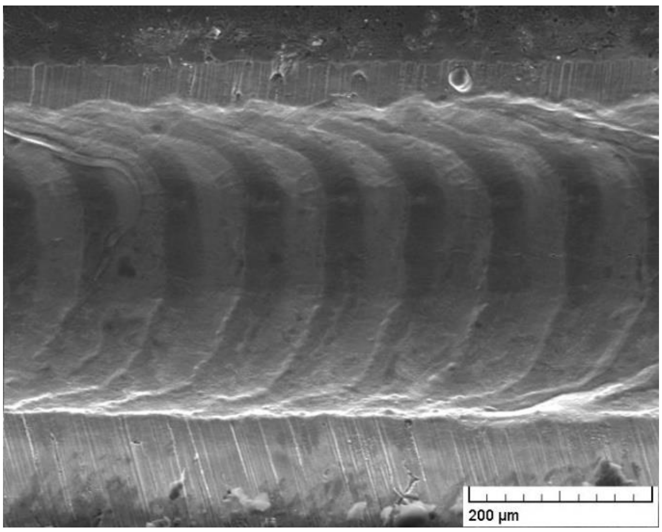
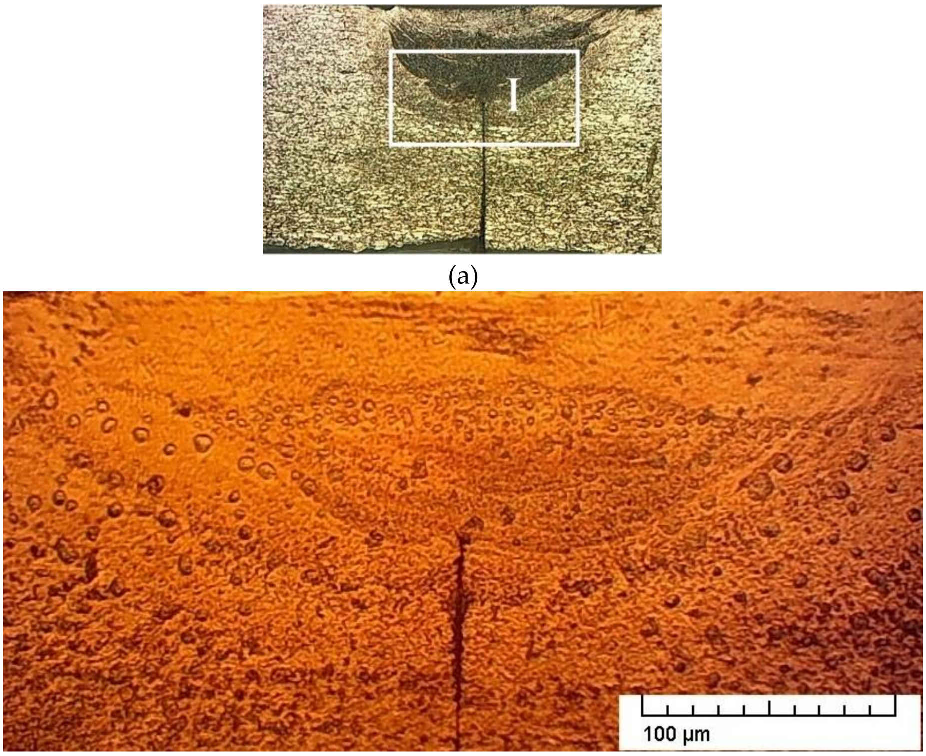


Figure 7. Top view of the welded joint, created by welding the three-layered MPM samples alternately on both sides.

The structure of the welded joints was examined on prepared samples after laser butt welding, which was carried out alternately on both sides. The samples were examined visually and using a Neophot-30 microscope (Carl Zeiss Jena GmbH, Jena, Germany). After the microsections were made, the surface was chemically etched. Figure 8 shows the etched macrosection of the weld and the microsection of the welded joint in the upper layer of the MPM sample. Oblique lighting was used to enhance a contrast. No coarse-grained cast structure was detected in the weld metal. The presence of microscopic cavities with foreign inclusions as well as very small single gas pores was also noted. No other weld defects were found in the examined samples. Welded joint samples in terms of geometric dimensions, grain size and localization of the weld joint line generally meet the requirements for ensuring the equal strength of the weld metal and the base metal.



(a)

(**b**)

Figure 8. (**a**) Macrosection of the weld; (**b**) microsection of the welded joint in the upper layer of the MPM sample, with an enlargement of the marked area I. Oblique lighting was used to enhance the contrast.

Macroscopic and microscopic examinations of the cross sections of all samples also showed that the weld pool morphology was practically symmetrical in relation to the laser beam axis. The hemispherical weld was formed in a similar way to conventional fusion welding processes. This symmetry was observed in all joints irrespective of the pulse energy, indicating a stable fluid flow in the weld pool. The dual phase steel microstructure of the base metal consisted of martensitic islands in ferrite matrix and is typical for this kind of steel. The microstructure of the heat affected zone was created under the effect of thermal weld cycle and represented martensite, bainite and retained austenite which were created by rapid cooling (Figure 9). In the region of the heat affected zone adjacent to the weld, the microstructure is finer in comparison to the microstructure of the melt pool, which is coarser. The analysis of weld microstructure showed directional orientation of dendrites with localization of opposite fronts of metal crystallization to the weld center. In the weld, isolated pores not exceeding 0.01 mm in size were observed. It is obvious that the detected micro defects based on size, shape and localization will not have a significant effect on the reduction of the mechanical characteristics of the welded joints.

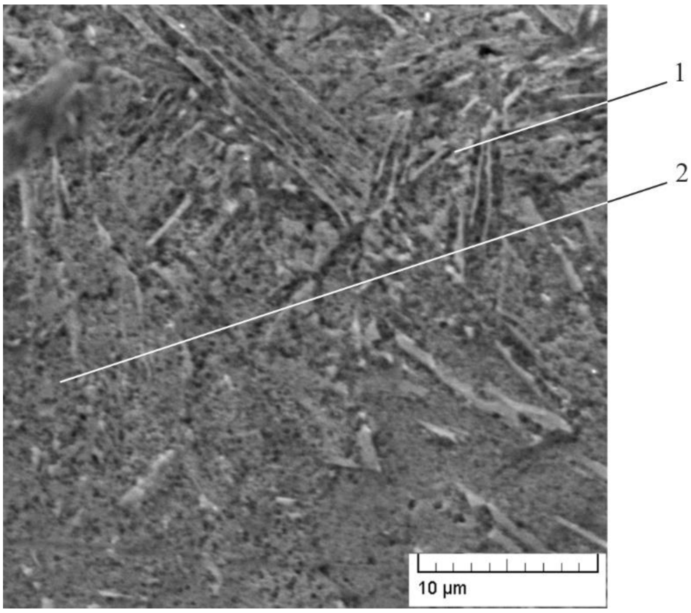


Figure 9. Cross-section image of a part of the heat affected zone obtained by a scanning electron microscope: 1—region of the melt pool; 2—heat affected zone adjacent to the weld bead.

All samples were laser welded in the heat conduction mode: direct heating and energy transfer. The direct heating mechanism involves the absorption of the beam energy by the surface and the subsequent transfer of energy to the surrounding material through thermal conduction. No significant amount of material was removed from the surface of the joint, meaning that the laser irradiation did not cause the material to reach the evaporation temperature. Characteristic welds were obtained by pulsed laser welding. By analyzing the surface, no welding cracks were detected in any of the welds. Practically no imperfections were observed in the weld metal. This can also demonstrate the effectiveness of the argon shielding gas used in preventing potential oxidation, large porosity and gas inclusions.

3. Discussion

Pulsed beam treatment resulted in a welded joint consisting of several points. For single-coordinate (linear or circular) contour-beam processing of materials with pulsed irradiation, the laser beam parameters, in particular pulse frequency and traverse speed, should be set to give a reasonably uniform penetration depth. The spacing cannot exceed the values at which unevenness in depth along the treatment contour significantly reduces the strength of the welded joint. If the spacing is selected small, the laser impact zones overlap, causing un-productive loss of laser pulse energy for reheating the already treated areas.

It is known that metal surfaces in the welding area must be cleaned of scale, rust and other contamination, as well as moisture. These contaminants and moisture create conditions for porosity, oxide inclusions and, in some cases, cold cracks in the metal of the weld, as well as in the heat affected zone due to hydrogen saturation. It is advisable to degrease the welding area as well. The same gases as for other welding methods can be used to protect the weld from oxidation. The best results in protecting the weld are achieved by helium or helium/argon mixtures. There are also recommendations to protect the weld surfaces from oxidation by a mixture of argon and carbon dioxide, fed through a special nozzle. In some welding applications it is acceptable to leave the weld unprotected.

Special process regimes that allow to reduce the requirements on the edges to be welded can be implemented. These regimes typically produce wider welds with lower edge alignment requirements. One of the easiest methods for obtaining a wide weld is by welding with defocusing using various optical systems [33]. The required penetration depth can be controlled by varying the laser power and adjusting the welding speed.

The redistribution of the beam power density can improve the structure of the welded joint. A variety of optical systems is possible to use to shape the laser beam. The main requirement is the simultaneous combination of such properties as the creation of a required power distribution and the concentration in the exposure area of the entire laser irradiation energy in a predefined shape. This can be achieved with diffractive freeform optics whose application is promising [34]. By shaping the laser energy that is selected at the calculation stage, these optical elements can create a predetermined intensity profile in the focal plane. Their application in laser material processing technology opens up entirely new possibilities for controlling the properties and operational characteristics of the materials under treatment [35].

Future studies can be focused on the investigation of the distribution of temperature fields in the MPM during laser treatment. This will help to adjust and optimize the processing parameters that are used for different parts. During laser welding of such materials, the main objective remains the reduction of significant degradation of the polymer core layer. Additional mechanical tests on the welded joints (e.g., durability, plasticity and toughness tests), as well as testing of the thermal insulation properties of the polymer core after heat treatment, will be necessary and help to optimize the parameters of laser welding of such composite materials.

4. Conclusions

Experimental studies on the possibility of laser welding of metal-polymer-metal composite materials were performed. The laser treatment was carried out by a Nd:YAG ROFIN StarWeld Manual Performance laser. The cross-sectional condition of the polymer layer and of the welded joint of the sample were investigated using a Neophot-30 microscope and a VEGA\\SB, Tescan scanning electron microscope. The performed research confirmed that laser welding alternately on both sides of the three-layered metal-polymer-metal samples made of DPK 30/50+ZE dual-phase steel as cover sheets that were electrolytic galvanized and a polypropylene-polyethylene foil as a core material can result in joints of both metallic layers, having high homogeneity of the metallographic structure as well as homogeneity of physical and mechanical properties. During laser welding of such materials, the main objective remains the reduction of significant degradation of the polymer core layer. Accordingly, the parameters of laser welding were chosen in such a way that the polymer structure remained almost unchanged. Significant improvements of the welding conditions are achieved by machining the edges of materials to be welded. The weld thickness was about 40% of the thickness of each steel layer. It was established that within the selected laser processing parameters the melting occurred uniformly, while the polymer layer practically did not change its structure.

Thus, it is determined that the implementation of the parameters of two-sided pulse-periodic laser welding, that is, for each of the two metal layers not throughout the entire thickness, but without significant degradation of the middle polymer layer, is possible. In this case, it is possible to realize laser welded joints, which will meet on the micro and macro level the basic requirements for relatively equal strength and serviceability imposed on sandwich materials.

The main goal for the development of the presented research is the improvement of the quality of the welded joint. Future studies can be focused on the investigation of the distribution of temperature fields in the metal-polymer-metal multilayer composite systems during laser treatment. This will help to adjust and optimize the processing parameters that are used for different parts. The redistribution of the beam power density can improve the structure of the welded joint. Application of diffractive freeform optics for laser treatment of materials may provide an opportunity to create a required set of properties of structural materials in the heat affected zone.

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preparation, S.P.M.; Writing—review and editing, S.P.M. and H.P.; Visualization, A.A.M. and M.V.B.; Supervision, S.P.M.; Project administration, S.P.M. and H.P.; Funding acquisition, S.P.M. and H.P. All authors have read and agreed to the published version of the manuscript.

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