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Surface Laser Micropatterning of Polyethylene (PE) to Increase the Shearing Strength of Adhesive Joints

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Abstract: In the introduction, we present an overview of previous research on this subject in order to help the reader review possible technological solutions regarding the joining of construction materials. The original research presented in this article concerns the results of increasing the shear strength of adhesive joints of plastics using various types of surface preparation (laser texturing). Laser texturing consists in developing the surface by applying various geometric patterns of appropriate shapes and depths, as well as its density on the surface. The above parameters are currently selected in an empirical way as research is still being developed as part of a research project. The textures obtained in this way are subjected to microscopic examination. Then, a layer of glue is applied, and the samples prepared in this way, after drying, are subjected to various destructive tests, e.g., tensile, shear, and bending. In this article, we attempted to test the strength of the bonded joint of polyethylene (PE). The impact of a laser beam with ultrashort picosecond pulses was used in the research. Tools in the form of a TRUMPF TruMicro 5325c device integrated with a SCANLAB GALVO scanning head were used. This enabled ablative material removal without the presence of a heat affected zone (HAZ) in the non-laser part. Ultrashort laser pulses remove material without melting the non-exposed area by the laser beam. On the basis of the tests performed (in this article and previous research works of the authors), it was shown that the method increases the shear strength of the glued joints made in the tested construction materials. This is confirmed by laboratory results of tribological tests. The laser treatment parameters used, which are shown in this article, did not lead to the appearance of cracks in the micromachined materials. Research has shown that the connections between elements with a properly selected micropattern are characterized by a several-fold increase in the strength of joints, unlike materials without a micropattern. The presented method may be helpful for use as a technology for joining plastics.

Keywords: UV laser; picosecond laser; adhesive joints; micromachining; micropatterning; polyethylene (PE); gluing; tear resistance

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1. Introduction

Laser technologies have been widely developed for over 20 years. Lasers have been used in metrology, surface treatment, etc. [1–5]. Lasers have significantly impacted manufacturing technologies in the automotive, aerospace, and electronics industries. Thanks to the rapid development of lasers, it is now possible to modify various surface layers and process various materials previously considered difficult to process for various reasons. Laser micromachining is becoming increasingly popular for modifying the surface properties of various construction materials [6–9]. Continuous improvement of existing design solutions results in using the latest achievements in material engineering, especially in the abovementioned industries. The effect of the impact of different types of laser beams on the surface of various materials has been studied in many scientific manuscripts [10,11].

These publications discussed the influence of different laser parameters (such as pulse frequency, light wavelength, pulse duration, etc.) on the surface of the laser-processed materials. Various techniques for modification of the surface by a laser beam of polymers have been discussed extensively in works [12,13].

Traditional methods of joining elements, such as screwing, riveting, and welding, are not always suitable for modern assembly, particularly for microelements. The use of mechanical fasteners always adds weight to the structure and can lead to increased production costs and can limit the types of materials to choose from or cause fatigue, strain, and even tearing. Bonding can outperform mechanical fasteners in many structural applications, providing clean and durable construction. Many industrial manufacturers are looking for industrial adhesives as an alternative to traditional bonding techniques. Thanks to achieving high reliability of objects, more and more products are made in the form of compact modules, in which the gluing technology is widely used.

The technique of modifying the surface of elements is used to improve the properties of materials. We call this technology surface texturing. It produces surface textures of various sizes and types with the desired properties to obtain the desired surface functionality. The influence of surface energy, capillarity, surface roughness, and whether the surface will have hydrophobic or hydrophilic properties affects the process of creating and breaking bonds in polymers [14]. The geometry of the texture itself also has a huge impact on the contact angle between the liquid droplet and the surface of the material, which in turn translates into appropriate adhesive properties [15–18].

Various surface texturing techniques have been developed in recent years, such as micromilling, electrochemical machining, hot embossing, lithography, ion beam etching, and mechanical and laser surface texturing [19–22]. Unlike other technologies, laser surface texturing is a noncontact, generally one-step technology. The advantages of laser surface texturing are the very high degree of material utilization, low heat affected zone, high process speed and universality of the tool, high quality of the final product, and low cost of production.

We distinguish several laser texturing technologies. The first one, laser ablation, removes the material and modifies the surface. Ablation takes place when the workpiece absorbs the energy from the laser radiation and the energy of its elementary particles is greater than the binding energy, which causes a phase change. The intensity and duration of the laser pulse, in common with the physical properties of a material, constitute a material's response to laser irradiation, resulting in miscellaneous mechanisms and schemes that guide the ablation of a material [23]. For ablation to happen, an energy threshold must be surpassed. The ablation mechanism largely depends on whether the focused laser beam absorbs energy in the surface layer of the substrate or material. Unlike metals, laser energy is absorbed by polymers in a nonlinear manner. Ablation involves both vaporization from the focal region and the ejection of molten material [18]. If the energy of the incident laser beam is lower than the ionization potential of the valence electrons bound to the polymer, no vaporization occurs. When free electrons collide with the high-energy photons of the laser beam (e.g., ultraviolet lasers), they absorb energy through collision in a process known as reverse bremsstrahlung (electromagnetic radiation produced by charged particles that pass through the electric and magnetic fields of an atomic nucleus and then accelerate or decelerate), leading to the breaking of chemical bonds [24]. With long laser pulses, this photon and electron excitation generates heat. It is possible to carry out the ablative process by photothermal or photochemical methods, or both at one time, depending on used laser technology parameters such as reflectivity, pulse duration, absorption coefficient, wavelength, and material properties [25]. In photothermal processes, the laser pulse's energy increases the material's surface temperature, resulting in melting or vaporization. Photothermal processes cause surface modifications such as polymer roughness. However, in photochemical processes, high-energy photons incident on the material's surface cause chemical modification by directly breaking down molecules. This is usually accomplished using lasers with wavelengths in the ultraviolet region of the optical spectrum. By combining photothermal and photochemical processes, surface roughness and chemical properties are changed simultaneously.

Another technique is the ablation threshold. We talk about threshold ablation when the material receives such an amount of energy that it will not lead to its ionization. A low ablation threshold means that as it were a little amount of energy is required to create recognizable changes on the surface of irradiated material. The ablation threshold decreases as repetitive laser pulses increase because of hatching impacts (i.e., consequent pulses are protected by the primary occurrence pulse). The most commonly studied polymeric substrates are PMMA (polymethyl methacrylate), PE (polyethylene), PC (polycarbonate), PTFE (polyfluoroethylene), and PI (polyimide) [26]. The commitment of hatching effects to ablation has been noticed during treatments of different polymers by femtosecond laser. The results uncovered a conversion within the transparent polymer absorption mechanism [27]. In single-pulse ablation, multiphoton absorption occurred. When multiple pulses were irradiated, the absorption mechanism became linear. In polymer substrates with a high fluence threshold (the energy of the laser pulse divided by the irradiated area indicates the laser energy concentration in J/cm^2) [28], a significant amount of energy is transferred to the material, causing heating, boiling, vaporization, and pore formation. In contrast, a small fraction of the laser energy exceeds the ionization region of the material.

On the other hand, the boiling phase is eliminated by allowing most of the pulse energy to remain above the ionization/material removal barrier. The porosity of the PE after laser surface treatment may be due to the rapid cooling of the very hot melt after intense boiling. Scanning electron microscopy images reveal the presence of pores in the microstructure formed by ablation with a femtosecond laser beam at a wavelength of 275 nm. In contrast to the homogeneous surface structure formed when irradiated with a laser beam at a 550 nm wavelength, different surface morphologies were observed when irradiated with a femtosecond laser beam at a 275 nm wavelength, which was attributed to the resolidification of the melt. The experimental results showed that the ionization threshold fluence increased with increasing wavelength, independent of the pulse number. A similar relationship led to the observation that homopolymers absorb laser energy better when irradiated with a 275 nm laser beam than an 800 nm laser beam, decreasing the ionization threshold fluence.

Laser surface texturing by direct writing, often called direct laser writing, is a flexible, high-precision, noncontact processing technique that uses a focused laser beam to draw complex structures over a large material surface area efficiently. It involves moving a focused laser beam in a line across the material's surface at a precise speed and number of pulses per point. Direct laser writing is defined as a 3D photolithographic technique in which the photoresist is solidified at the focus of the laser beam to create very small features [29]. A similar technique is direct laser interference patterning, which can create multiple features within a single spot. Laser beam micromachining is a similar technology that utilizes the properties of a laser beam to create microfeatures on the material surface to control the surface integrity of the target material and prevent damage [30]. In this technique, a cylindrical vector beam produces primary microstructures, which are then decorated with secondary submicron ripples. The height of the generated microcones and the distance between features can be varied by changing the angle of incidence and the overlap of the pulses. Multiscale frequency-structured surfaces exhibit remarkable wetting properties and are used in various applications [21].

Ultrashort pulsed lasers are used in laser microfabrication applications due to their high energy density and provide accurate laser-induced distortion thresholds at reinduced fluences. Other advantages of ultrashort pulsed lasers include reduced thermal effects and damage, high spatial resolution, and improved quality of ablated features. Ultrashort pulsed laser processing of transparent materials with intense field ionization is possible due to the high peak intensity of the ultrashort pulses. Intense field ionization is the first step of multiphoton ionization and is mostly associated with intense optical laser fields of short duration [30]. The main disadvantage of direct laser writing is the difficulty in producing fine surface features at high speed: Millions of convex microlens arrays on PMMA have been produced by femtosecond direct laser writing [31]. The fabrication process was based on in situ modification of a single femtosecond pulse without using a mask or replicated template. The authors achieved their goal by developing an efficient approach to create convex microlens arrays over large areas of the PMMA layer. At pulse energies below the damage threshold, the absorption mechanism was mostly due to multiphoton and avalanche ionization.

Further laser irradiation resulted in the cleavage of the polymer chains. Localized swelling was observed in regions of the PMMA surface exposed to direct laser irradiation [32]. Moreover, when the pulse energy was increased to a threshold value, the smooth surface quality of some stable microlenses was maintained until ablation started to occur. Pits formed at the top of the domed microlenses and grew as the ablation increased. The ejection of material formed the crater due to plasma formation [31]. Changes in impact energy affect the degree and type of surface modification that can be achieved on polymer surfaces. An elongated pattern of ablation craters was observed at higher impact energies [33]. The results show that the ablation craters formed at higher pulse energies move in the direction of the polarization of the laser beam. Asymmetric ablation craters are produced by linear and elliptical polarization at two times the threshold fluence, while symmetric craters are produced by circular polarization.

Direct laser interference patterning is an efficient surface texturing technique that interacts with coherent laser beams on material surfaces to create high-resolution, periodic structural patterns. This technique is effective for rapidly patterning large surface areas with features down to the nanometer scale [34,35]. The direct laser interference patterning process offers greater flexibility in the target material and texture geometry choice. Direct laser interference patterning methods can produce complex dot and line patterns, as the feature shape and spatial period are determined by the number, intensity, or polarization of the laser beam used and changes in the interference angle of the incident beam. Direct laser interference patterning methods effectively process various materials and create sophisticated structures for various applications, including optoelectronics, microlens fabrication, advanced nanorod growth, moisture sensing, and tissue engineering for scaffold fabrication [35–39].

The authors of this manuscript describe the possibilities of using laser microsurface strengthening to obtain stronger adhesive bonds for selected construction materials. Polyethylene (PE) and Multibond 1101 epoxy glue were used for the tests. Polyethylene is an artificial, thermoplastic material characterized by low water vapor permeability and high resistance to acids, bases, salts, and temperatures. Polyethylene is a material belonging to the group of polyolefins, i.e., polymers that consist only of carbon and hydrogen. $CH_2{=}CH_2$ mers form it. Due to its unique properties, polyethylene has many different applications. It can be used, among others, to make pipes, containers, and even sails. During the COVID-19 pandemic, the demand for this material increased, especially for producing transparent barriers. Polyethylene accounts for approximately 30% of all plastics, meaning approximately 60 million tons are produced annually [40].

The adhesive agent used for the tests and the procedure for preparing the surface of the joined construction materials, as described below, were performed in the same way as in the previous tests described by the authors in paper [41].

MULTIBOND-1101 works well in heavily loaded structures exposed to temperature, chemicals, water, etc. Typical applications are automotive components and machine parts, components of railway cars, buses, and yachts.

Sides of the processed material had a micropattern made with a picosecond laser. The goal was to achieve a better mechanical connection. The overarching goal of this study was to develop an innovative joint solution that can reduce energy consumption in the machining process and provide a better joint. After the tests, the effect of the preshaped PE surface was presented, and the strength tests of the process of joining the surface with a micropattern and the surface without a micropattern were discussed. It has been shown that the joints of elements with a properly processed microstructure are characterized by a repeatable increase in the strength of the joints, unlike materials without a microstructure.

This manuscript aims to present the impact of the type of laser-machined microtexture on the material's surface on increasing the adhesive force in adhesive joints. In addition, this study addresses practical solutions to the adhesive method used for joining the polymers used for tests. This study could be helpful for each application where we have to connect these types of polymers.

2. Materials and Methods

The mechanical, thermal, and electrical properties of polyethylene used for the tests (ARMET, Katowice, Poland) are shown in Table 1 [42].

Table 1. The mechanical, thermal, and electrical properties of polyethylene.

Property	Value	Unit
Abrasion (sand suspension)	≥90	%
Stress at the yield point	≥18–20	MPa
Elongation	~300	%
Young modulus, E	~700	MPa
Impact strength (Charpy)	>120	kJ/m^2
Thermal conductivity at 23 °C	>0.40	W/m K
Puncture resistance	~40	KV/mm
Surface resistance	$>10^{12}$	Ω

The main properties of MULTIBOND-1101 (Multibond Sp. Z o.o, Sp.k, Lodz, Poland) are shown in Table 2 [43].

Table 2. MULTIBOND-1101 properties [43].

Property	Value	Unit
Viscosity (before it hardens)	10,600 (component A) 6300 (component B)	mPa·s
Specific weight in 25 °C (before it hardens)	1.16 (component A) 0.98 (component B)	g/mL
Shear strength with tensile strength (after it hardens)	26.0 (metals) 7.0 (plastics)	N/mm^2
Peel-off resistance (after it hardens)	5.0	N/mm
Working temperature range	−60–+100	°C

Micromachining of materials was carried out on a laboratory stand equipped with a picosecond laser TRUMPF 5325c with a wavelength of 343 nm and a maximum average power of 5 W. The scanning head of the SCANLAB intelliSCAN 14 (SCANLAB GmbH, Puchheim, Germany) was used for position laser beam in the working area. Prior to the laser micropattern, the sample surface was cleaned with ethanol. The results of the microtreatment research are shown in the images taken using the HIROX KH-8700 digital microscope (Hirox Co., Ltd., Tokyo, Japan) (Figure 1).

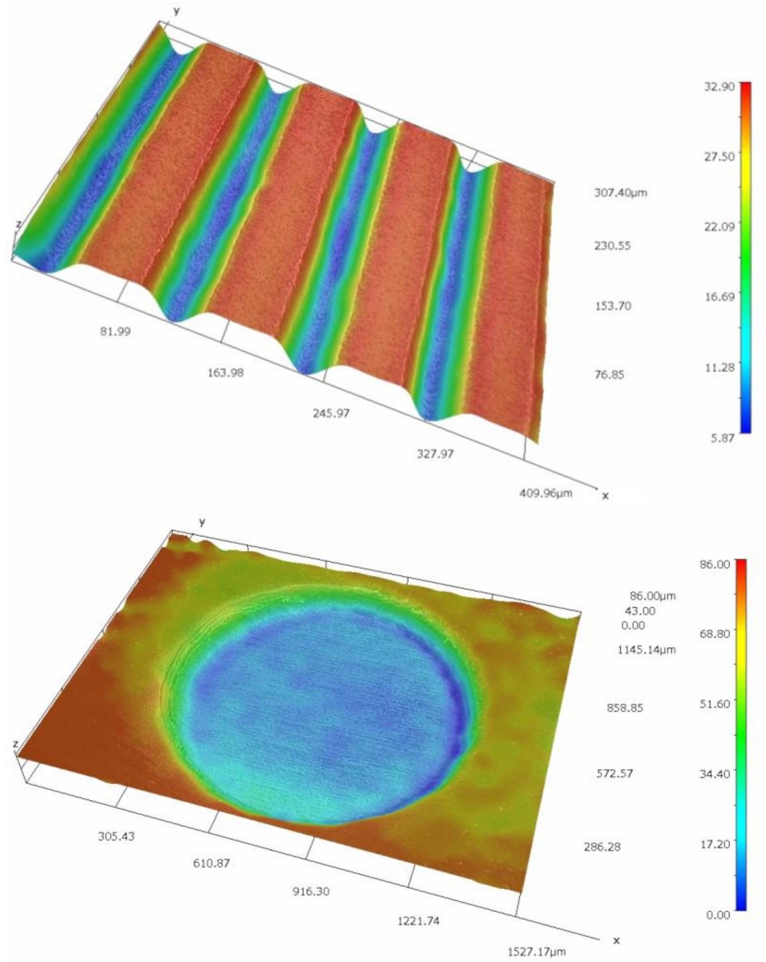

Figure 1. General view of micropatterns, such as parallel lines and circles on the sample surface.

After laser micromachining, the samples were washed in an ultrasonic cleaner with ethanol and then with deionized water. Then, the lap joint between the materials was made using Multibond 1101 epoxy adhesive. The diagram of lap connection is presented and depicted underneath in Figure 2.

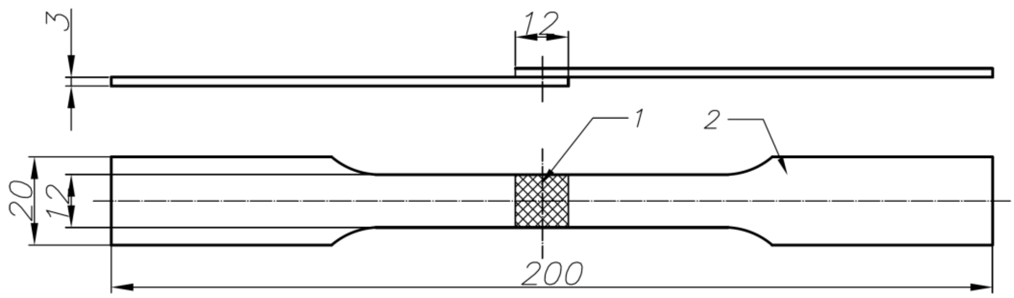

Figure 2. Lap connection diagram: 1 is the zone of laser microprocessing, and 2 is the zone of fixing the sample in the jaws of the testing machine.

Figure 3 presents photographs of samples during the subsequent phases of the gluing process with the use of a holder stabilizing their position in relation to each other. Figure 3A—one part of the sample placed and stabilized in the holder, Figure 3B—samples pressed with a spacer insert and glue applied, Figure 3C—the second part of the sample placed in a spacer insert and pressed in the joint area. The holder allows the simultaneous gluing of 5 samples.

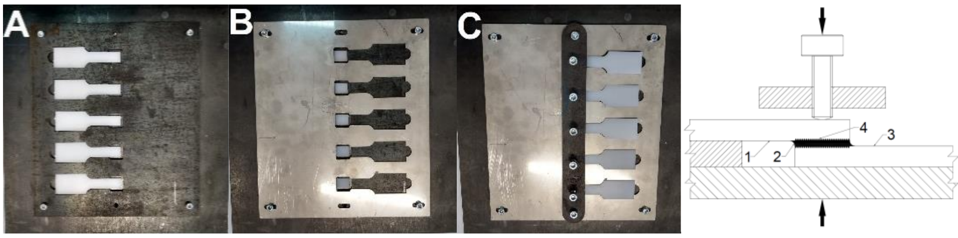

Figure 3. View the successive phases of gluing samples placed in a holder specially designed for this purpose and the connection scheme.

The spacer insert ensures the assumed thickness of the adhesive layer (0.1 or 1 mm). After applying the binder, the samples were immobilized in the holder (Figure 3) until the glue was completely set (approximately 24 h, according to the manufacturer's declaration). In the connection diagram shown in Figure 3, 1 and 3—textured sample, 2—glue, and 4—textured area on the joined samples. The arrows indicate the pressure.

The INSTRON 4502 machine (Norwood, MA, USA) was used for strength tests according to PN-EN ISO 291:2010 Standard [44]. This allowed us to determine to what extent the micromachining of the selected geometric shape influenced the increase in the force needed to break the joint.

3. Results

The tests carried out were aimed at examining which type of micropattern had a significant impact on increasing the strength of glued joints and at the same time did not affect the surface properties of the material. The microstructure changes the properties of the top layer of the material. It allows for better surface development and greater adhesive penetration, which affects adhesive strength. Improper micropatterning can make the surface hydrophobic, making it difficult to adhere the adhesive agent to the material surface. The authors chose two common shapes, circles and parallel lines, as shown in Figure 1.

Figure 4 shows a cross-section of the joint area, where it can be observed that the adhesive penetrated thoroughly into the laser-made microtexture, which significantly increased the adhesion strength of the joint.

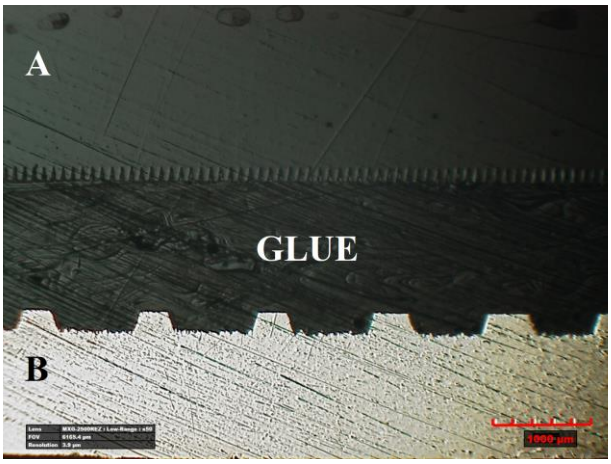

Figure 4. Sample view of the cross-section of the joint area. (**A**) Surface with a linear microstructure. (**B**) Surface with a circular microstructure. Hirox KH-8700 digital microscope (Hirox Co., Ltd., Tokyo, Japan).

The desired effect of micromachining was obtained by the ablative removal of material from the sample surface [10] by linear movement of the laser beam. Further studies on other types of polymers predict other types of depth, density, and shape of the laser-made micropattern. Table 3 shows the parameters for laser processing on the TRUMPF TruMicro 5325c (Trumpf GmbH, Ditzingen, Germany).

Table 3. Treatment parameters.

Property	Value	Unit
Pulse energy	12.6	µJ
Pulse repetition frequency	200	kHz
Laser scanning speed	1000	mm/s
Shielding gas (air)	12	nl/min

According to the above parameters, samples for gluing were made on the surface of which microstructures in the form of parallel lines perpendicular to the direction of the breaking force, and a texture in the form of circles was created. The lines were made at a distance of approximately 80 µm and with an average depth of 30 µm. The microtexture with circles covered approximately 50% of the surface to be glued. The diameter of a single element was approximately 1 mm, and its average depth was 70 µm. The density and distribution of the micropatterns were selected based on empirical research conducted by the authors of this manuscript.

Surface preparation is crucial to ensure a durable and stable adhesive joint, regardless of the type of adhesive used. The adhesion rate between the substrate and the adhesive largely influences the strength of the joint. Contaminated surfaces impair adhesion and require cleaning to ensure optimal bonding. Before the laser micromachining process, each sample was cleaned with isopropanol. Just before bonding, the samples were blasted with compressed air to remove any residual material. The samples prepared in this way were glued in a specially designed device, which allowed us to obtain a constant and repeatable thickness of the adhesive joint of approximately 1 mm. This provided visual control of the bonding. Additional pressure was not needed. The samples were allowed to dry completely for 24 h under normal room conditions. A general view of the joined sample before destruction is shown in Figure 5. Then, the samples were placed in the jaws of the INSTRON 4502 testing machine (Norwood, MA, USA), and strength tests were performed. After performing the connection-breaking tests, microphotographs showed the appearance of the connection surface after destruction (Figure 6).

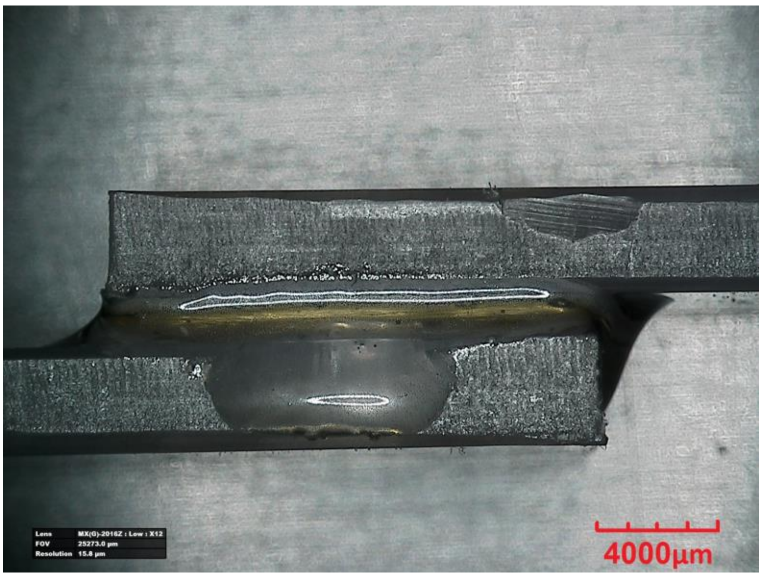

Figure 5. General view of the joined sample before destruction. Hirox KH-8700 digital microscope (Hirox Co., Ltd., Tokyo, Japan).

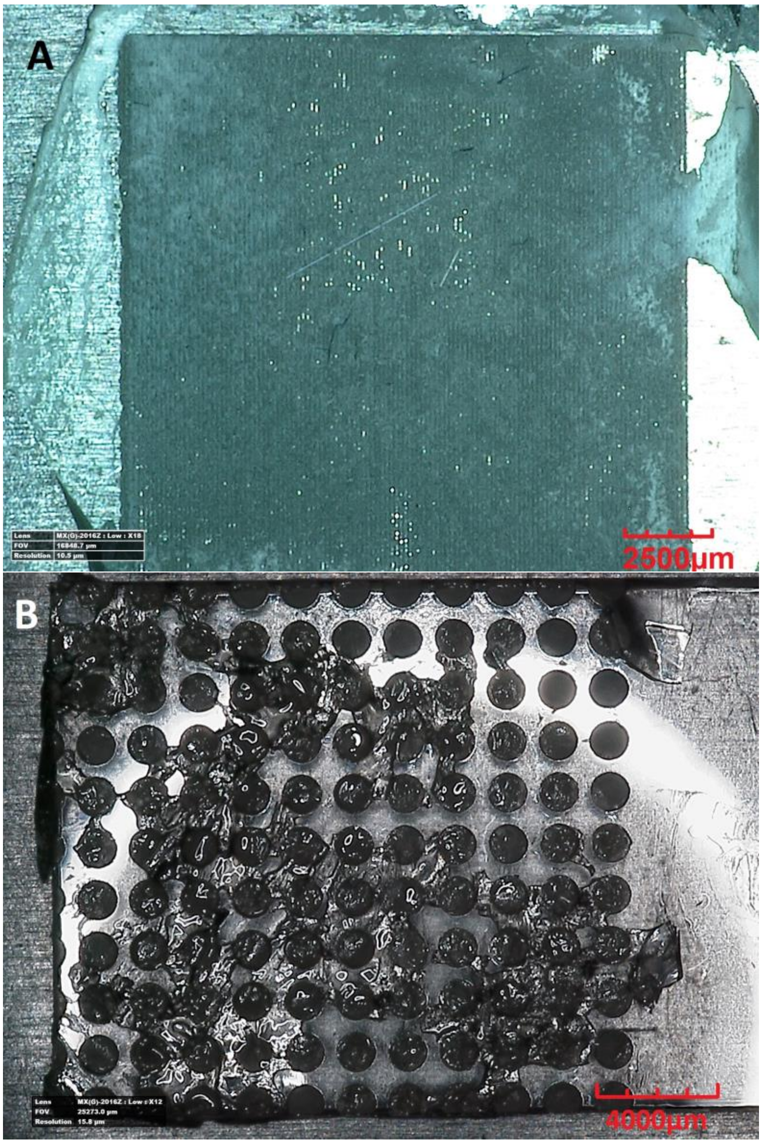

Figure 6. (**A**) General view of the sample's surface with a texture of lines after destruction. (**B**) General view of the sample of the joint with a circular texture after destruction. Hirox KH-8700 digital microscope (Hirox Co., Ltd., Tokyo, Japan).

The tensile test consisted of uniaxial deformation, during which force measurements were recorded. This type of research allowed us to obtain a basic range of information about the tribological properties of plastics and adhesive joints. The results of these tests included deformation (elongation) and deformation force (breaking force). The tensile strength of a joint is the maximum stress that a material can withstand during static stress. The study was carried out for five samples with a microstructure and five without a microstructure [41].

The texture was made on the surface of 12 × 12 mm on one side of the joined elements. Glue was applied to the textured zone, and a lap joint was created, which is marked in the diagram [41]. The sample for the static tensile test was prepared in accordance with the requirements of the PN-EN ISO 6892-1 standard [45]. Table 4 compares the average breaking strength results of the joint made and the value of the increase in strength of the joint with texture in relation to the joint without texture.

Table 4. Average joint breaking strength results.

	PE without Micropattern	PE with Circle Micropattern	PE with Perpendicular Lines Micropattern
Measurement 1, N	55	145	252
Measurement 2, N	42	134	235
Measurement 3, N	56	140	241
Measurement 4, N	48	138	249
Measurement 5, N	50	149	255
Average, N	50.2	141.2	246.4
Standard deviation, N	5.67	5.89	8.23
Min, N	42	134	235
Max, N	56	149	255
The average increase in strength, %	-	281.27	490.84

Figure 7 illustrates the tensile force of the formed joint. No plastic flow of the sample was observed due to the brittle fracture of the applied adhesive and the tested material.

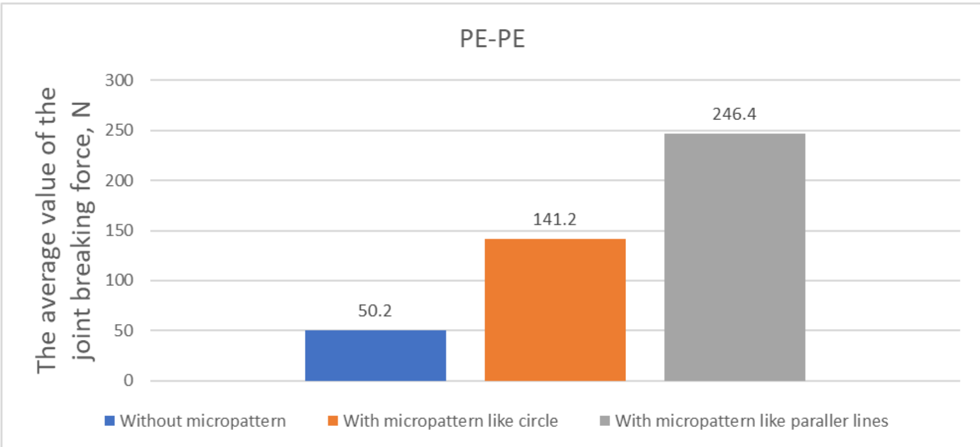

Figure 7. The tensile force of the formed joint.

Samples glued without microtexturing cracked with an average tensile force of 50.2 N. Samples glued with a circular structure failed with an average force of 141.2 N, while samples with a linear texture broke at an average force of 246.4 N. Compared to samples without microtexture, the average force needed to break a sample adhesively bonded to a circular microtexture is 281.27% higher. On the other hand, the samples connected adhesively with the microtexture in parallel lines were destroyed with an average breaking force of 490.84%, compared to samples without microtexture.

4. Discussion

A significant number of polymers are inherently either hydrophobic or only slightly hydrophilic. Fortunately, they can be rendered hydrophilic at least temporarily by exposure to a laser beam. The laser micromachining method is sufficient to obtain hydrophilic surface properties. Making appropriate geometric shapes (micropattern) can increase the hydrophilic properties of the polymer surface. The microtexture also increases the surface of the glued material, which increases the adhesion surface and thus the force needed to break the joint. Improper preparation of microtextures affects the change in the value of the contact angle and thus changes the surface energy of the material. In connection with the above, additional tests should be performed, allowing for a more accurate analysis of the results obtained. Despite small discrepancies, we obtained satisfactory results from the perspective of conducting further research on modifying micropatterns shape and density parameters. We proved that the correct modification of both the operating parameters of the laser device and the microtexture will allow for even more durable glued joints. Appropriate use of the operating parameters of the laser device, as well as changing the geometrical properties of the pattern, are of great importance for the properties of the adhesive joint. These properties are closely correlated with each other. A small change in one operating parameter of the laser device or the geometric properties of the micropattern can significantly affect the final result of the process. Earlier publications of the authors contain more detailed information on changes in the properties of materials after laser micromachining [13,46].

5. Conclusions

Tests have proven that the type of microtexture significantly impacts the creation of a more durable adhesive connection using a laser micropattern on the surface of the glued material. In the case of a PE material, a surface connection with a microtexture shows a significantly higher tear resistance in a static tensile test than the same connection without a surface pattern. During the tests, it was shown that the obtained linear microtexture had the best adhesive properties. The circular structure also had better adhesive properties than untextured samples but was approximately two times lower than the linear structure. Laser micropatterning on the surface is a very promising method of creating more favorable hydrophilic conditions for better wetting of adhesives.

We are in the process of performing further strength tests for other types of adhesive joints in other configurations of material pairs: metal–plastic, ceramic–plastic, and metal–ceramic. Joints will be made with or without a textured surface and with or without any other type of adhesive.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Pietraszek, J.; Radek, N.; Goroshko, A.V. Challenges for the DOE methodology related to the introduction of Industry 4.0. *Prod. Eng. Arch.* **2020**, *4*, 190–194. [CrossRef]
2. Radek, N.; Szczotok, A.; Gądek-Moszczak, A.; Dwornicka, R.; Bronček, J.; Pietraszek, J. The impact of laser processing parameters on the properties of electrospark deposited coatings. *Arch. Metall. Mater.* **2018**, *63*, 809–816.
3. Kurp, P. Ideas and Assumptions of a New Kind Helical Metal Expansion Joints. *Mater. Res. Proc.* **2022**, *24*, 236–242.
4. Gądek-Moszczak, A.; Radek, N.; Wroński, S.; Tarasiuk, J. Application the 3D image analysis techniques for assessment the quality of material surface layer before and after laser treatment. *Adv. Mater. Res.* **2014**, *874*, 133–138. [CrossRef]
5. Lasagni, A.F.; Roch, T.; Berger, J.; Kunze, T.; Lang, V.; Beyer, E. To use or not to use (direct laser interference patterning), that is the question. *Proc. SPIE* **2015**, *9351*, 935115.
6. Mao, B.; Siddaiah, A.; Liao, Y.; Menezes, P.L. Laser surface texturing and related techniques for enhancing tribological performance of engineering materials: A review. *J. Manuf. Process.* **2020**, *53*, 153–173. [CrossRef]
7. Garcia-Giron, A.; Romano, J.M.; Batal, A.; Dashtbozorg, B.; Dong, H.; Solanas, E.M.; Angos, D.U.; Walker, M.; Penchev, P.; Dimov, S.S. Durability and Wear Resistance of Laser-Textured Hardened Stainless Steel Surfaces with Hydrophobic Properties. *Langmuir* **2019**, *35*, 5353–5363. [CrossRef]
8. Romano, J.-M.; Garcia-Giron, A.; Penchev, P.; Dimov, S. Triangular laser-induced submicron textures for functionalising stainless steel surfaces. *Appl. Surf. Sci.* **2018**, *440*, 162–169. [CrossRef]

9. Krzywicka, M.; Szymańska, J.; Tofil, S.; Malm, A.; Grzegorczyk, A. Surface Properties of Ti6Al7Nb Alloy: Surface Free Energy and Bacteria Adhesion. *J. Funct.Biomater.* **2022**, *13*, 26. [CrossRef]
10. Witkowski, G.; Tofil, S.; Mulczyk, K. Effect of laser beam trajectory on pocket geometry in laser micromachining. *Open Eng.* **2020**, *10*, 830–838. [CrossRef]
11. Antoszewski, B.; Sęk, P. Influence of laser beam intensity on geometry parameters of a single surface texture element. *Arch. Met. Mater.* **2015**, *60*, 2215–2219. [CrossRef]
12. Romano, J.-M.; Gulcur, M.; Garcia-Giron, A.; Martinez-Solanas, E.; Whiteside, B.R.; Dimov, S.S. Mechanical durability of hydrophobic surfaces fabricated by injection molding of laser-induced textures. *Appl. Surf. Sci.* **2019**, *476*, 850–860. [CrossRef]
13. Antoszewski, B.; Tofil, S.; Mulczyk, K. The Efficiency of UV Picosecond Laser Processing in the Shaping of Surface Structures on Elastomers. *Polymers* **2020**, *12*, 2041. [CrossRef] [PubMed]
14. Ravi-Kumar, S.; Lies, B.; Zhang, X.; Lyu, H.; Qin, H. Laser ablation of polymers—A review. *Polym. Int.* **2019**, *68*, 1391–1401. [CrossRef]
15. Prakash, J.C.G.; Prasanth, R. Approaches to design a surface with tunable wettability: A review on surface properties. *J. Mater. Sci.* **2021**, *56*, 108–135. [CrossRef]
16. Milles, S.; Voisiat, B.; Nitschke, M.; Lasagni, A.F. Influence of roughness achieved by periodic structures on the wettability of aluminum using direct laser writing and direct laser interference patterning technology. *J. Mater. Process. Technol.* **2019**, *270*, 142–151. [CrossRef]
17. Shen, M.-X.; Zhang, Z.-X.; Yang, J.-T.; Xiong, G.-Y. Wetting Behavior and Tribological Properties of Polymer Brushes on Laser-Textured Surface. *Polymers* **2019**, *11*, 981. [CrossRef] [PubMed]
18. Singh, A.; Patel, D.S.; Ramkumar, J.; Balani, K. Single step laser surface texturing for enhancing contact angle and tribological properties. *Int. J. Adv. Manuf. Technol.* **2019**, *100*, 1253–1267. [CrossRef]
19. Ruszaj, A.; Cygnar, M.; Grabowski, M. The state of the art in electrochemical machining process modeling and applications. *AIP Conf. Proc.* **2018**, *2017*, 020029. [CrossRef]
20. Patil, D.; Sharma, A.; Aravindan, S.; Rao, P.V. Development of hot embossing setup and fabrication of ordered nanostructures on large area of polymer surface for antibiofouling application. *Micro Nano Lett.* **2019**, *14*, 191–195. [CrossRef]
21. Wang, R.; Wei, J.; Fan, Y. Chalcogenide phase-change thin films used as grayscale photolithography materials. *Opt. Express* **2014**, *22*, 4973–4984. [CrossRef]
22. Kim, C.-S.; Ahn, S.-H.; Jang, D.-Y. Review: Developments in micro/nanoscale fabrication by focused ion beams. *Vacuum* **2012**, *86*, 1014–1035. [CrossRef]
23. Gamaly, E.G. The physics of ultrashort laser interaction with solids at nonrelativistic intensities. *Phys. Rep.* **2011**, *508*, 91–243. [CrossRef]
24. Avino, P.; Petrucci, A.; Schulze, D.; Segebade, C.; Activation, A.A.-P.; Worsfold, P.; Poole, C.; Townshend, A.; Miró, M. *Encyclopedia of Analytical Science*, 3rd ed.; Academic Press: Cambridge, MA, USA, 2019; pp. 25–39. [CrossRef]
25. Antoszewski, B.; Kurp, P. Effect of Surface Texture on the Sliding Pair Lubrication Efficiency. *Lubricants* **2022**, *10*, 80. [CrossRef]
26. Assaf, Y.; Kietzig, A.-M. Optical and chemical effects governing femtosecond laser-induced structure formation on polymer surfaces. *Mater. Today Commun.* **2018**, *14*, 169–179. [CrossRef]
27. Wood, M.J.; Coady, M.J.; Aristizabal, F.; Nielsen, K.; Ragogna, P.J.; Kietzig, A.-M. Femtosecond laser micromachining of copolymeric urethane materials. *Appl. Surf. Sci.* **2019**, *483*, 633–641. [CrossRef]
28. Ocaña, J.L.; Morales, M.; Porro, J.A.; Díaz, M.; de Lara, L.R.; Correa, C. *Laser Plasma Interaction and Shock Material Processing*; Hashmi, S., Batalha, G.F., Van Tyne, C.J., Yilbas, B., Eds.; Comprehensive Materials Processing; Elsevier: Amsterdam, The Netherlands, 2014; pp. 47–74. [CrossRef]
29. Zhang, Q.; Dong, J.; Peng, M.; Yang, Z.; Wan, Y.; Yao, F.; Zhou, J.; Ouyang, C.; Deng, X.; Luo, H. Laser-induced wettability gradient surface on NiTi alloy for improved hemocompatibility and flow resistance. *Mater. Sci. Eng. C* **2020**, *111*, 110847. [CrossRef]
30. Kulander, K.; Lewenstein, M. *Multiphoton and Strong-Field Processes*; Drake, G., Ed.; Springer Handbook of Atomic, Molecular, and Optical Physics, Springer Handbooks; Springer: New York, NY, USA, 2006. [CrossRef]
31. Ou, Y.; Yang, Q.; Chen, F.; Deng, Z.; Du, G.; Wang, J.; Bian, H.; Yong, J.; Hou, X. Direct Fabrication of Microlens Arrays on PMMA With Laser-Induced Structural Modification. *IEEE Photonics Technol. Lett.* **2015**, *27*, 2253–2256. [CrossRef]
32. Kallepalli, L.N.D.; Soma, V.R.; Desai, N.R. Femtosecond-laser direct writing in polymers and potential applications in microfluidics and memory devices. *Opt. Eng.* **2012**, *51*, 073402. [CrossRef]
33. Guay, J.-M.; Villafranca, A.; Baset, F.; Popov, K.; Ramunno, L.; Bhardwaj, V.R. Polarization-dependent femtosecond laser ablation of poly-methyl methacrylate. *New J. Phys.* **2012**, *14*, 085010. [CrossRef]
34. Voisiat, B.; Aguilar-Morales, A.I.; Kunze, T.; Lasagni, A.F. Development of an Analytical Model for Optimization of Direct Laser Interference Patterning. *Materials* **2020**, *13*, 200. [CrossRef]
35. Alamri, S.; Lasagni, A. Development of a general model for direct laser interference patterning of polymers. *Opt. Express* **2017**, *25*, 9603–9616. [CrossRef]
36. Lasagni, A.; Manzoni, A.; Mücklich, F. Micro/Nano Fabrication of Periodic Hierarchical Structures by Multi-Pulsed Laser Interference Structuring. *Adv. Eng. Mater.* **2007**, *9*, 872–875. [CrossRef]
37. Zhai, T.; Zhang, X.; Pang, Z.; Dou, F. Direct Writing of Polymer Lasers Using Interference Ablation. *Adv. Mater.* **2011**, *23*, 1860–1864. [CrossRef]

38. Stankevičius, E.; Malinauskas, M.; Gedvilas, M.; Voisiat, B.; Račiukaitis, G. Fabrication of periodic microstructures by multiphoton polymerization using the femtosecond laser and four-beam interference. *Mater. Sci.* **2011**, *17*, 244–248. [CrossRef]
39. Nemani, S.K.; Annavarapu, R.K.; Mohammadian, B.; Raiyan, A.; Heil, J.; Haque, M.A.; Abdelaal, A.; Sojoudi, H. Surface Modification of Polymers: Methods and Applications. *Adv. Mater. Interfaces* **2018**, *5*, 1801247. [CrossRef]
40. Zhong, X.; Zhao, X.; Qian, Y.; Zou, Y. Polyethylene plastic production process. *Insight-Mater. Sci.* **2018**, *1*, 1–8. [CrossRef]
41. Tofil, S.; Manikandan, M.; Arivazhagan, N. Surface Laser Micropatterning of Polyethylene Terephthalate (PET) to Increase the Shearing Strength of Adhesive Joints. *Mater. Res. Proc.* **2022**, *24*, 27–33.
42. Available online: https://www.armetpolska.pl/pe-polietylen/ (accessed on 14 June 2023).
43. MULTIBOND-1101 Data Sheet. Available online: www.multibond.pl (accessed on 14 June 2023).
44. *PN-EN ISO 291:2010;* Tworzywa sztuczne—Znormalizowane Warunki Klimatyczne Kondycjonowania I Badania, (in English—Plastics—Standardized Climatic Conditioning And Testing). PKN (Polski Komitet Normalizacyjny): Warsaw, Poland, 2010.
45. *PN-EN ISO 6892-1:2020-05*; Próba Rozciągania—Część 1: Metoda Badania W Temperaturze Pokojowej (in English—Tensile test—Part 1: Test Method At Room Temperature). PKN (Polski Komitet Normalizacyjny): Warsaw, Poland, 2022.
46. Tofil, S.; Barbucha, R.; Kocik, M.; Kozera, R.; Tański, M.; Arivazhagan, N.; Yao, J.; Zrak, A. Adhesive Joints with Laser Shaped Surface Microstructures. *Materials* **2021**, *14*, 24. [CrossRef]