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Comparative Adhesion of Anaerobic and Cyanoacrylate Adhesives to Hydrophilic Surface on Mild Steel

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Abstract: This study is about laser-induced surface activated DC01 and S235 mild steels, which are bonded with an anaerobic acrylic adhesive (Loctite 270) and a cyanoacrylate adhesive (Loctite 496). A fiber laser was used with 50–100% power, 20–200 kHz pulse frequencies, and scanning speeds were 500–2000 mm/s. Wettability was measured by water contact angle (WCA), and the joint performance was examined through single-lap shear tests. Both untreated steels showed hydrophobic behaviour (DC01: 72.9°, S235: 89.8°), which resulted in low shear strengths: 0.29 kN (DC01, acrylic), 2.03 kN (DC01, cyanoacrylate), 0.57 kN (S235, acrylic), and 0.06 kN (S235, cyanoacrylate). After laser treatment, the WCA was under 5° in most cases, showes complete wetting. This change was reflected in a significant increase in strength. In the case of DC01, the acrylic adhesive achieved 2.9 kN (≈10×) and the cyanoacrylate achieved 5.6 kN (≈2.5×). In the case of S235, the acrylic adhesive achieved 3.9 kN (≈7×), while the cyanoacrylate increased from 0.06 to 6.1 kN (≈100×). Based ont he results the laser activation can create a clean, highly hydrophilic surface. It increases the adhesion of both adhesive systems. Although the two steels responded differently to the treatment, in all cases the reduction in the rim angle was closely related to the increased bond strength.
Keywords: Steel, surface treatment, laser, wettability, adhesive.

Összefoglalás: A kutatás célja a lézerrel indukált felületaktiválás hatásának vizsgálata DC01 és S235 lágyacélok nedvesedési tulajdonságaira és ragasztott kötéseinek szilárdságára. A mintákat két különböző ragasztórendszerrel – anaerob akrilát (Loctite 270) és cianoakrilát (Loctite 496) ragasztóval – kötötték össze. A felületkezelést impulzusüzemű szállézerrel végezték 50–100% teljesítmény, 20–200 kHz impulzusfrekvencia és 500–2000 mm/s pásztázási sebesség tartományában. A felületi nedvesedést peremszögméréssel, a ragasztott kötések kötésszilárdságát egylapos nyíróvizsgálattal értékelték.

A kezeletlen acélfelületek hidrofób viselkedést mutattak (DC01: 72,9°, S235: 89,8°), ami alacsony kötési szilárdságot eredményezett. A lézeres felületaktiválás hatására a peremszög a legtöbb esetben 5° alá csökkent, ami teljes nedvesedést jelez. A hidrofíl felület kialakulása jelentős szilárdságnövekedést eredményezett mindkét ragasztórendszer esetében. DC01 acélon az akril ragasztó szilárdsága közel tízszeresére (≈2,9 kN), a cianoakriláté pedig mintegy 2,5-szeresére (≈5,6 kN) nőtt. S235 acélon az akril ragasztó körülbelül hétszeres (≈3,9 kN), míg a cianoakrilát ragasztó több mint százszoros (≈6,1 kN) szilárdságnövekedést mutatott. Az eredmények igazolják, hogy a lézeres felületaktiválás hatékony módszer hidrofíl, nagy felületi energiájú acélfelületek létrehozására, amely jelentősen javítja a ragasztott kötések tapadását és ipari alkalmazhatóságát.
Kulcsszavak: Acél, felületkezelés, lézer, nedvesíthetőség, ragasztó.

Introduction

Adhesive bonding has become an important joining method in many manufacturing sectors, for example automotive, energy and construction. Compared with welding or mechanical fastening, the adhesive joints distribute loads more evenly, support lightweight design, and allow the joining of dissimilar materials. This technic do not introduce thermal distortion or galvanic corrosion. Industries shift toward cleaner and more efficient production and the demand for reliable, solvent-free bonding processes seems to grow. This trend is reinforced by sustainability expectations in the transport sector. Vehicle impact is now judged mainly through lifecycle CO_2 emissions and the energy mix that supports their operation. The performance of adhesive joints on mild steels, depends strongly on the condition of the surface. Materials such as DC01 and S235 typically carry native oxides, rolling residues and adsorbed hydrocarbons, that's why the surface energy is lower and block molecular-level contact with the adhesive. Conventional surface preparation methods, such as mechanical abrasion, chemical etching or solvent cleaning, can improve adhesion. These methods often suffer from inconsistency, environmental concerns, or difficulties in automation. Laser-based surface treatment offers a precise and clean alternative. Controlled laser irradiation can remove contaminants, renew oxide layers, and create micro- and nano-scale textures that raise surface energy and promote wetting. These changes are especially important for adhesives whose curing mechanisms rely on surface chemistry. Anaerobic acrylic adhesives, for example, require metal ions to initiate polymerization, while cyanoacrylates depend mainly on surface polarity and moisture. Both the chemical state and the microstructure of the steel surface affect their final bonding performance. This paper aim is to examine how laser-induced surface activation affects the wettability and adhesive strength of bonded DC01 and S235 steels with an anaerobic acrylic (Loctite 270) and a cyanoacrylate adhesive (Loctite 496). By comparing untreated and laser-treated surfaces, the study aims to clarify how changes in surface energy and surface chemistry translate into mechanical performance, and to identify process conditions that support clean, repeatable and industrially applicable adhesive bonding.

Literature Review

The significance of structural adhesive bonding of steels

Structural adhesive bonding has become a key method for lightweight and hybrid constructions. Adhesive joints spread the load across a larger area, allowing thinner components without compromising strength, and this is the main difference compared to welding or mechanical fastening. In the latter mentioned technologies local stresses, heat-affected zones and distortion can introduce [1]. This is especially valuable in automotive body structures, transport applications, and various civil or energy systems where weight reduction and fatigue resistance play an important role. Adhesive bonding also makes it possible to join dissimilar materials without the risk of galvanic corrosion or metallurgical incompatibility [2]. Because the process does not involve high temperatures, it avoids phase changes and residual stresses that commonly occur in welded joints, improving dimensional stability and fatigue performance [3]. Recent studies show that hybrid solutions, where spot welds are combined with structural adhesives, can enhance crash behaviour and corrosion resistance in vehicle bodies, supporting their use in mass production [4]. Despite these benefits, steel-to-steel adhesive bonding is still limited in industry, mainly because surface preparation strongly influences long-term reliability. Native oxides, rolling lubricants and adsorbed hydrocarbons form weak layers that reduce surface energy and inhibit proper molecular contact with the adhesive [1]. Reliable bonding therefore requires controlled, consistent surface activation. As a result, research has increasingly shifted from developing new adhesive formulations toward refining surface engineering techniques that render steel surfaces more chemically active and hydrophilic. Among the most promising approaches are plasma treatments, chemical activation and various laser-based methods, all capable of removing weak surface layers and producing stable, high-energy surfaces suitable for modern adhesives [3]. These developments are also in line with broader sustainability evaluations in the European transport sector, where the environmental performance of both electric and conventional vehicles depends strongly on national energy mixes and lifecycle CO_2 emissions [5, 6].

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Laser surface treatment as a clean and controllable pre-treatment to improve adhesion

Laser surface treatment has become a strong alternative to traditional cleaning and activation methods such as grit blasting, chemical etching or plasma treatment. The industrial popularity of the laser surface treatment comes from its environmental advantages and consistent performance [7]. Chemical processes depend on solvents or generate waste, but laser activation is a dry, contactless method. It can be fully controlled and easily integrated into automated production lines [8]. Pulsed laser radiation interacts with metal surfaces. It produces localized melting, rapid solidification and renewal of the oxide layer. These effects remove weak boundary layers and increase surface energy. The process parameters are average power, pulse frequency and scanning speed, can form different micro- and nano-scale textures. These are modifying wetting and adhesion in a characteristic way [9]. Several studies show that even moderate laser energy can reduce the water contact angle (WCA) of metallic surfaces from roughly 80–90° to below 10°. In many cases the WCA reduced to <5°, resulting in a superhydrophilic surface that strongly favours adhesive wetting [10]. A major benefit of laser pre-treatment is its dual effect: it alters the surface chemistry, while also shaping the microstructure. The laser removes hydrocarbons and it promotes the formation of a thin, hydroxyl-rich oxide layer containing Fe–O–OH groups, so the polar component of surface free energy increased [11]. At the same time, microgrooves or microcones form on the surface. These are increasing the real contact area and supporting mechanical interlocking with the adhesive [12]. These combined changes typically lead to more stable and reproducible adhesion than what is achievable with purely chemical or mechanical preparation. Results from steel–epoxy, steel–acrylic and steel–cyanoacrylate joints show that once the WCA falls below about 10°, shear strength increases sharply, often reaching 300–400% improvement compared with untreated surfaces [13].

Influence of adhesive chemistry on the effectiveness of laser surface activation

There are many adhesives, such as anaerobic acrylics, cyanoacrylates, epoxies, and polyurethanes, which can interact differently with metallic surfaces depending on their functional groups, polymerization kinetics, and sensitivity to surface chemistry [14]. Anaerobic acrylic adhesives, typically based on dimethacrylate esters, cure in the absence of oxygen and in the presence of metal ions (e.g., Fe^{2+}, Cu^{2+}), which act as radical initiators. The bonding strength of anaerobic systems is highly sensitive to surface cleanliness and the availability of catalytically active metal sites [15]. Laser treatment can improve these conditions by removing passive oxide layers and exposing fresh metallic iron. Polymerization can be faster and increases the density of interfacial crosslinking. However, too much laser energy may create thick, stoichiometric oxide films. These layers reduce the availability of metal ions and can hinder curing—a behaviour reported in several recent studies on steel substrates [16]. Cyanoacrylate adhesives polymerize through an anionic moisture-induced mechanism, which does not require metallic ion activation. Instead, their performance depends primarily on surface polarity and the presence of hydroxyl or carboxyl functional groups. These groups can facilitate electron transfer and rapid polymerization initiation [17]. Laser activation, by increasing the surface's hydroxyl group density and producing hydrophilic Fe–O–OH terminations, provides ideal conditions for cyanoacrylate curing [18].

The aim of this study is to investigate the effect of laser-induced surface activation on the adhesion performance of anaerobic (acrylic) and cyanoacrylate adhesives applied to mild steels (DC01 and S235). By comparing the changes in surface wettability, chemistry, and resulting shear strength, the research seeks to clarify how laser parameters influence the interfacial bonding mechanisms of two chemically distinct adhesive systems. The goal is to identify energy-efficient, solvent-free, and industrially applicable pre-treatment conditions that enhance adhesive reliability and performance in structural steel bonding applications.

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Materials and Methodes

S235 steel specimens

The research used S235 structural steel which is a commonly used low-carbon steel grade. It is a standard construction material in mechanical and structural engineering. It was selected because it represents a typical mild steel base material, which is frequently used during industrial adhesive bonding. This material is a relevant steel for researching about adhesion performance under engineering conditions. Rectangular specimens were cold cutted from cold-rolled S235 sheets with a thickness of 1 mm. The samples were cut into 25×100 mm specimens. Before the surface treatment the steel specimens were cleaned with ethanol to ensure that the surfaces were free from oil, dust, and other contaminations. The cleaned specimens were stored in a closed container to prevent further contamination before the surface treatment and adhesive bonding.

DC01 steel specimens

The second base material in this study was DC01 cold-rolled mild steel, which is a low-carbon, high-purity steel grade. Commonly used in automotive applications. DC01 was selected because of low alloying content. Compared with S235 structural steel the DC01 has a less oxidized surface layer and a more homogenous surface. This allows a better base surface for laser induced surface modifications, wettability change and adhesion test. The specimens were prepared from the same way and geometry as S235. It was 1 mm thick DC01 sheets and cut into 25×100 mm samples. The specimens were cleaned with ethanol again.

Laser surface treatment

Surface treatment process of the DC01 and S235 steel specimens was carried out using a JPT MOPA M7 fiber laser system. It is equipped with a 30 W average output fiber laser source with a wavelength of 1064 nm. This device operates in the nanosecond pulse range. The laser beam was moved and focused on the specimen surface using a galvanometric scanning head with a f-theta lens, ensuring high-speed and controlled laser energy irridation on the treated area. The laser surface treatment process was under ambient atmospheric conditions without the use of gases. The average beam power was changed between 50% and 100% of the maximum average laser power. The pulse frequency was changed between 20 and 200 kHz, the scanning speed between 500 and 2000 mm/s.

These parameter combinations created different laser surface energy densities and this research can investigate its effect on surface activation. The laser beam was moved in linear hatch patterns, with a spacing of 0.05 mm, covering the later adhesive bonding area of each specimen.

Contact angle measurement

Surface wettability was measured using a contact angle measurement equipment. The measurement is based on the sessile drop method. The machine was equipped with a high-resolution optical camera and image-processing software for precise measurement of static contact angles on the liquid droplets. The contact angle measurements were performed using 5 µl droplets of distilled water as test fluid. The droplets were dispensed onto the treated steel surfaces after one minute of the laser surface activation. It was to minimize the effect of time dependence of the wetting behaviour. Each water droplet image was captured immediately after spreading on the surface, and the left and right contact angles were measured and averaged, this average value shows the surface wettability state in each treatment parameter.

Adhesive applying method

The adhesive bonding experiments were carried out on the DC01 and on the S235 steel specimens. Both two steels were used to investigate the effect of laser induced surface activation on the adhesive bonding performance and strength. The steel bonding were designed in a single-lap shear configuration. Each specimen had a overlap area of 25 x 12.5 mm, corresponding to a bonded surface of 312.5 mm2.
Two different adhesive type were used to represent different curing mechanisms and chemical interactions with the metallic surfaces:

- an anaerobic acrylic adhesive (Loctite 270), which cures in the absence of oxygen and in the presence of active metal ions,
- a cyanoacrylate adhesive (Loctite 496), which cures rapidly in the activation effect of surface moisture.

Loctite 270 is a dimethacrylate ester–based anaerobic adhesive that polymerizes in the absence of oxygen and in the presence of active metal ions. Its curing mechanism depends strongly on the surface chemistry of the substrate, where the most important is that how much the metallic surfaces containing Fe^{2+} or Cu^{2+} ions. These adhesives are used for common metal-metal bondings, for threadlocking, surface sealing. Loctite 496 is a methyl cyanoacrylate adhesive that cures rapidly through anionic polymerization triggered by the surface moisture.

Unlike the type of anaerobic adhesives, it does not require metal ions and it is more tolerant of non-metallic or passive surfaces. Its bonding strengths is highly dependent on the wetting behaviour and the polarity of the surfaces.

For each overlapped adhesive joints 0.050 g of adhesive was applied on the cleand and laser surface treated area. The opposite side of the bonding area was carefully positioned to achieve full overlap without entrapping air bubbles. The specimens were pressed together using a custom alignment fixture ensuring parallel bonding surfaces and controlled press during curing.

The joints were cured under ambient laboratory conditions (22–23 °C, 45–55% RH) for 72 hours, allowing complete curing.

Results

Wetting changing effect of the laser treatment

In this section the modification effect of laser surface activation on the wettability of the two investigated steel substrates, the DC01 mild steel and the S235 structural steel as analysed. This is the first step to understand the adhesive bonding strength behaviour. A lower water contact angle (WCA) means that the surface is hydrophilic and it is has high surface free energy and it is an activated surface. It is the favourable for strong adhesion.

The high contact angle means that the surface has a hydrophobic conition. It can be contaminated or it is a passivated surface. The poor wetting state limits the connection of surface adhesive bonds. The results of the laser surface treatment on S235 structural steel are summarized in *Table 1*.

Table 1. Water contact angle (WCA) of S235 steel surfaces before and after laser surface treatment at different laser powers, pulse frequencies, and scanning speeds.

Material	Average laser beam power (%)	Laser beam pulse frequency (kHz)	Scanning speed (mm/sec)	Water contact angle, WCA (°)
S235	Untreated			89.75
S235	Untreated			89.75
S235	50%	200	500	<5
S235	50%	200	500	<5
S235	50%	200	2,000	34.35
S235	50%	200	2,000	34.35
S235	60%	20	500	9.95
S235	60%	20	500	9.95
S235	60%	20	500	9.95
S235	80%	20	500	<5
S235	80%	20	500	<5
S235	80%	20	500	<5
S235	90%	20	500	<5
S235	90%	20	500	<5
S235	90%	20	500	<5
S235	100%	20	500	<5
S235	100%	20	500	<5
S235	100%	20	500	<5
S235	100%	200	500	<5
S235	100%	200	500	<5
S235	100%	200	2,000	16.3
S235	100%	200	2,000	16.3

The untreated S235 surface had a high water contact angle of approximately 89.8.° It has a hydrophobic and poorly wettable metallic surface. This high contact angle can be the presence of a thick iron oxide film (Fe_2O_3/Fe_3O_4) combined with adsorbed hydrocarbons and organic contaminations. This creates a reduced surface energy and inhibit polar interactions with water.

After the laser surface activation the decrease of WCA was observed using nearly all laser surface treatment parameter combinations. It is confirming the strong influence of the laser treatment on surface wettability and polarity. In several cases using higher laser powers the contact angle decreased to below 5°. This impulse laser surface treatment can create hydrophilic state on the S235. In these cases the water droplet spread instantaneously across the surface. It is preventing accurate conact angle measurement during the tests therefore, such conditions were marked as “<5.°”

It is a signifying total spread of water on the surface. This hydrophilic phenomenon was observed for 80–100% laser power using both low (20 kHz) and high (200 kHz) pulse frequencies. This suggests that above a higher laser surface irridation energy density the S235 surface becomes fully activated, which will be good for adhesive bonding.

At medium power laser surface parameters (60% power, 20 kHz, 500 mm/s) the contact angle values were still reduced (around 10°) indicating that the surface wetting is partial. Higher WCA were measured at lower laser power or faster laser beam scanning speeds (34° at 50% power and 200 kHz with 2000 mm/s). The reduced energy input limited the oxide layer modification and surface activation. This tendency shows that the energy density is the dominant parameter controlling the wetting behaviour on the S235 surface. This can be explained by a combination of surface cleaning, oxidation, and microstructural modification of the surface induced by the pulsed laser beam radiation. The high local temperature and rapid cooling creates a thin, homogenous, high-energy oxide layer. It can be enriched in hydroxyl (–OH) and oxygen-containing functional groups. These modifications significantly increase the polar component of surface energy leading to increased wettability and high surface free energy. The micro and nano texturing and micro-roughness generated by the impulse laser beam irridation creates the hydrophilic behaviour. It is increasing the real contact area between the water droplet and the surface (Wenzel effect).

The wettability test results for the DC01 steel substrates are summarized in *Table 2.*

Table 2. Water contact angle (WCA) of DC01 steel surfaces before and after laser surface treatment at different laser powers, pulse frequencies, and scanning speeds.

Material	Average laser beam power (%)	Laser beam pulse frequency (kHz)	Scanning speed (mm/sec)	Water contact angle, WCA (°)
DC01	Untreated			72.9
DC01	Untreated			72.9
DC01	50%	200	500	<5
DC01	50%	200	500	<5
DC01	50%	200	2,000	7.3
DC01	50%	200	2,000	7.3
DC01	100%	20	500	<5
DC01	100%	20	1,000	<5
DC01	100%	20	1,000	<5
DC01	100%	20	2,000	<5
DC01	100%	20	2,000	<5
DC01	100%	200	500	<5
DC01	100%	200	500	<5
DC01	100%	200	2,000	<5
DC01	100%	200	2,000	<5

The DC01 mild steel specimens shows that the laser surface treatment can cause a change in the surface wettability. It can be seen by the significant reduction in the water contact angle (WCA) nearly in every laser treatment parameter. The untreated DC01 surface has an initial contact angle of 72.9° which is a bad wetting state and a hydrophobic surface. It is typical for cold-rolled steels containing a thin oxide layer and trace organic residues from rolling or handling processes.

The laser surface activation decreased the water contact angle across all tested parameter combinations. The WCA values went to below 5° in most cases. The reduction in contact angle confirms the strong activation effect of the laser treatment. The laser treatment cleaned, oxidized, and micro-textured the steel surface.

Using moderate (50%) laser power and high (100%) laser powers created a good wettability. The intermediate laser beam energy densities can be used to induce surface polarity changes in DC01 steels. Slight variations happened at the highest scanning speeds (2000 mm/s). In this case the water contact angle increased to around 7°. It shows only a little change because of the reduced local energy input. At lower scanning speeds (500–1000 mm/s) and higher pulse frequencies (200 kHz) the surfaces consistently had full surface wetting activation. This change is connected to a combination of thermal oxidation and remove of hydrocarbon contaminants and micro-scale surface roughening induced by the laser pulses. In this case too, like in the case of S235 the localized heating created a thin oxide layer enriched in hydroxyl (–OH) groups.

S235 and DC01 steels both became highly hydrophilic and had a good wetting condition on its surfaces. After the laser treatments DC01 showed a faster decrease in water contact angle from ~73° to below 5° even at medium laser beam power. It shows easier surface activation conditions. While the activation of S235 required higher laser beam energy to reach the same hydrophilic state. It had partial surface wetting activation (10–35°) at medium laser beam power level parameters. This difference could come from the more complex and more stable oxide layer on S235, which is harder to modify than the thin, easily oxidized surface of DC01.

Shear strength of the joints

For S235 steel the adhesive joint strength results can be seen in *Table 3.*

Table 3. Effect of laser-induced surface activation on the water contact angle (WCA) and maximum shear strength of S235 steel joints bonded with acrylic and cyanoacrylate adhesives.

Adhesive	Material	Average laser beam power (%)	Laser beam pulse frequency (kHz)	Scanning speed (mm/sec)	Water contact angle, WCA (°)	Average - Maximum shear force values (kN)	Scatter - Maximum shear force values (kN)
Acrylic	S235	Untreated			89.8	0.57	0.63
Acrylic	S235	50%	200	500	<5	3.95	0.46
Acrylic	S235	50%	200	2,000	34.4	3.11	0.69
Acrylic	S235	60%	20	500	10.0	3.59	0.40
Acrylic	S235	60%	20	500	10.0	3.43	0.66
Acrylic	S235	80%	20	500	<5	2.96	0.60
Acrylic	S235	80%	20	500	<5	3.12	0.29
Acrylic	S235	90%	20	500	<5	2.33	1.04
Acrylic	S235	90%	20	500	<5	3.16	0.50
Acrylic	S235	100%	20	500	<5	2.24	1.44
Acrylic	S235	100%	20	500	<5	1.92	1.77
Acrylic	S235	100%	200	500	<5	3.85	0.20
Acrylic	S235	100%	200	2,000	16.3	3.63	0.33
Cyanoacrylate	S235	Untreated			89.8	0.06	0.13
Cyanoacrylate	S235	50%	200	500	<5	5.64	0.63
Cyanoacrylate	S235	50%	200	2,000	34.4	5.07	0.78
Cyanoacrylate	S235	60%	20	500	10.0	2.21	1.17
Cyanoacrylate	S235	80%	20	500	<5	4.99	0.54
Cyanoacrylate	S235	90%	20	500	<5	4.33	0.79
Cyanoacrylate	S235	100%	20	500	<5	4.40	0.48
Cyanoacrylate	S235	100%	200	500	<5	6.15	0.66
Cyanoacrylate	S235	100%	200	2,000	16.3	5.33	1.54

These results show a clear and consistent correlation between surface wettability and maximum shear force. It confirms that laser improved wetting can change significantly the adhesive bonding performance for both adhesive types. For the untreated S235 surface which had a high contact angle (90°) and low surface energy both adhesives resulted in poor adhesion. The anaerobic acrylic adhesive achieved an average shear strength of 0.57 kN, while the cyanoacrylate adhesive showed 0.06 kN. The 0.06 kN comes from the fact that sometimes the force measurement was failed because the specimens were broke before the start of the measurement, they fractured only handling them.

After laser surface activation the shear strength increased in both cases. When the contact angle decreased below 5° and reached complete wetting the acrylic adhesive reached force values between 3.0–3.9 kN, and the cyanoacrylate adhesive between 5.0–6.2 kN. This resulted approximately a six times increase for the acrylic adhesive and nearly a two orders of magnitude improvement for the cyanoacrylate adhesive compared with the untreated S235 steel surfaces.

While both adhesives benefited from higher surface energy on the steels their effect to laser surface parameters is different. The acrylic adhesive showed higher strength at moderate to high laser power (50–100%) and 500 mm/s scanning speed. Its performance tended to slightly decrease at the highest laser power levels. This shows that the energy input can lead to local over oxidation on the surface producing thicker oxide films. It is reduce metal ion availability which is critical for the anaerobic curing mechanism.

The cyanoacrylate adhesive showed a more monotonic and stable improvement durring the tested laser parameter conditions. Since this adhesive cures using moisture-induced anionic reactions, its adhesion is primarily depend on surface polarity and wetting. The highest strength values (6.1 kN) were measured at 100% power, 200 kHz, and 500 mm/s, where the surface was fully hydrophilic.

The adhesive bonding results of DC01 mild steel confirms the strong correlation between laser surface activation, contact angle reduction and shear strength improvement for both adhesives. These results can be seen in *Table 4.*

Table 4. Effect of laser-induced surface activation on the water contact angle (WCA) and maximum shear strength of DC01 mild steel joints bonded with acrylic and cyanoacrylate adhesives.

Adhesive	Material	Average laser beam power (%)	Laser beam pulse frequency (kHz)	Scanning speed (mm/sec)	Water contact angle, WCA (°)	Average - Maximum shear force values (kN)	Scatter - Maximum shear force values (kN)
Acrylic	DC01	Untreated			72.85	0.29	0.31
Acrylic	DC01	50%	200	500	<5	2.10	0.84
Acrylic	DC01	50%	200	2,000	7.25	1.62	0.70
Acrylic	DC01	100%	20	500	<5	2.96	0.24
Acrylic	DC01	100%	20	1,000	<5	2.47	0.46
Acrylic	DC01	100%	20	2,000	<5	2.07	0.47
Acrylic	DC01	100%	200	500	<5	2.88	0.19
Acrylic	DC01	100%	200	2,000	<5	2.33	0.26
Cyanoacrylate	DC01	Untreated			72.85	2.03	1.23
Cyanoacrylate	DC01	50%	200	500	<5	5.62	0.54
Cyanoacrylate	DC01	50%	200	2,000	7.25	4.60	0.51
Cyanoacrylate	DC01	100%	20	1,000	<5	4.39	0.36
Cyanoacrylate	DC01	100%	20	2,000	<5	4.85	0.48
Cyanoacrylate	DC01	100%	200	500	<5	5.15	0.10
Cyanoacrylate	DC01	100%	200	2,000	<5	5.07	0.35

The untreated DC01 surface, had a water contact angle of 72.9°, showed poor wettability and correspondingly low adhesion strength. In this state, the anaerobic acrylic adhesive reached an average shear strength of only 0.29 kN, while the cyanoacrylate adhesive achieved 2.03 kN. These low values reflect the limited surface energy and the presence of organic residues and native oxides that inhibit wetting and chemical bonding.

After laser surface treatment, the adhesives demonstrated an increase in bond strength, directly associated with the reduction of the contact angle to below 5°, indicating a transition to a superhydrophilic surface state. The anaerobic acrylic adhesive showed an average shear strength between 2.1 and 2.9 kN, corresponding to roughly a ten-times improvement compared to the untreated condition. The highest adhesion (2.96 kN) was obtained at 100% laser power and 20 kHz, while slightly lower but still consistent results were observed across other parameter combinations. The improvement can be attributed to the removal of oxides and contaminants, exposure of catalytically active metal ions, and the formation of a micro-textured surface that enhances both chemical polymerization efficiency and mechanical interlocking.

The cyanoacrylate adhesive showed even greater sensitivity to surface activation. Upon laser treatment, the shear strength increased from 2.03 kN to values between 4.4 and 5.6 kN, representing approximately a 2.5-fold enhancement. The highest adhesion values (~5.6 kN) corresponded to surfaces with contact angles below 5°, confirming that the adhesive's performance is strongly governed by surface polarity and wetting. Unlike the anaerobic system, the cyanoacrylate adhesive did not depend on metallic ions for curing, and therefore achieved consistent strength across all activated surfaces, even at high scanning speeds.

Connection between the chemical of the adhesive, the steels and surface treatment

The combined analysis of laser-treated and untreated specimens showes that the interaction between adhesive chemistry, steel substrate, and surface wettability governs the final bonding performance. The summary and comparation *Table 5.* results show consistent trends across all measurements: laser-induced surface activation-manifested by a sharp reduction in water contact angle-produced significant increases in adhesive joint strength for both DC01 and S235 steels, though the extent and mechanism of improvement were strongly dependent on both the adhesive type and the substrate composition.

Table 5. Average and individual shear strength values of acrylic and cyanoacrylate adhesive joints on DC01 and S235 mild steel substrates before and after laser-induced surface activation, including corresponding water contact angles and relative strength improvements compared to untreated surfaces

Adhesive	Material	Average laser beam power (%)	Laser beam pulse frequency (kHz)	Scanning speed (mm/sec)	Water contact angle, WCA (°)	1. Repetition - Maximum shear force value (kN)	2. Repetition - Maximum shear force value (kN)	3. Repetition - Maximum shear force value (kN)	4. Repetition - Maximum shear force value (kN)	5. Repetition - Maximum shear force value (kN)	Average - Maximum shear force values (kN)	Scatter - Maximum shear force values (kN)	Average strength increase due to surface treatment to Untreated material
Acrylic	DC01	Untreated			72.85	0	0	0.72	0.27	0.47	0.29	0.31	Reference
Acrylic	S235	Untreated			89.75	0	1.06	1.39	0.39	0	0.57	0.63	Reference
Cyanoacrylate	DC01	Untreated			72.85	0.47	1.33	2.48	2.15	3.74	2.03	1.23	Reference
Cyanoacrylate	S235	Untreated			89.75	0	0	0.02	0	0.3	0.06	0.13	Reference
Acrylic	DC01	50%	200	500	<5	0.63	2.2	2.71	2.59	2.36	2.1	0.84	724%
Acrylic	S235	50%	200	500	<5	3.76	3.46	3.85	4.7	3.97	3.95	0.46	693%
Cyanoacrylate	DC01	50%	200	500	<5	4.89	5.66	5.45	5.71	6.39	5.62	0.54	277%
Cyanoacrylate	S235	50%	200	500	<5	6.29	5.27	5.08	6.36	5.18	5.64	0.63	9400%
Acrylic	DC01	50%	200	2,000	7.25	0.53	1.72	1.82	1.53	2.48	1.62	0.7	724%
Acrylic	S235	50%	200	2,000	34.35	3.81	3.35	3.08	1.97	3.36	3.11	0.69	546%
Cyanoacrylate	DC01	50%	200	2,000	7.25	5.46	4.5	4.59	4.28	4.15	4.6	0.51	227%
Cyanoacrylate	S235	50%	200	2,000	34.35	5.03	4.28	6.38	4.84	4.82	5.07	0.78	8450%
Acrylic	DC01	100%	200	500	<5	2.8	2.61	3.05	2.89	3.05	2.88	0.19	993%
Acrylic	S235	100%	200	500	<5	3.62	4.13	3.86	3.7	3.93	3.85	0.2	675%
Cyanoacrylate	DC01	100%	200	500	<5	5.17	5.09	5.19	5.02	5.27	5.15	0.1	254%
Cyanoacrylate	S235	100%	200	500	<5	5.98	6.31	6.54	5.1	6.81	6.15	0.66	10250%
Acrylic	DC01	100%	200	2,000	<5	2.36	2.49	2.03	2.12	2.65	2.33	0.26	803%
Acrylic	S235	100%	200	2,000	16.3	3.86	3.62	3.75	3.85	3.07	3.63	0.33	637%
Cyanoacrylate	DC01	100%	200	2,000	<5	5.19	4.93	4.55	5.2	5.48	5.07	0.35	250%
Cyanoacrylate	S235	100%	200	2,000	16.3	5.35	5.24	7.87	4.3	3.91	5.33	1.54	8883%

Influence of Laser Activation on S235 Steel

The untreated S235 structural steel showed a higher contact angle ~89.8°, which provides a very poor adhesion in its untreated state. Using the acrylic adhesive the untreated case achieved only 0.57 kN, while the cyanoacrylate adhesive failed to join the surfaces (0.06 kN), in this state the specimens fractured during handling for the strength test. These low joint strengths can be explained by the chemically inert and unremoved oxide layer on S235.

The laser surface activation improved the wettability of S235 with contact angles of under 5° using most conditions. The adhesion strength increased by several orders of magnitude. With the acrylic adhesive the average shear strengths were between 3.1 and 3.9 kN, it leads to a 700% improvement to the untreated surface. The cyanoacrylate adhesive, however, showed higher improvement with the strength values increasing from 0.06 kN to over 5.6 kN, equivalent of 9000% improvement.

This massive improvement can be because of the the chemical sensitivities of the two adhesive systems. The anaerobic acrylic adhesive cures on metal-ion activation and it has benefits from moderate oxidation and micro-roughening. The cyanoacrylate adhesive strengths depend mainly on the surface polarity and moisture.

Influence of Laser Activation on DC01 Steel

The untreated DC01 mild steel had a hydrophobic surface with a water contact angle of 72.9°, the untreated specimens showed low initial bonding strength. The anaerobic acrylic adhesive (Loctite 270) bonded only with 0.29 kN, while the cyanoacrylate adhesive (Loctite 496) reached 2.03 kN. This weak performance of the acrylic adhesive can be because of the the presence of a passive oxide film and adsorbed hydrocarbons. After the laser surface activation, the contact angle went below 5°. The adhesion strength of both adhesives increased very high. Using the acrylic adhesive the average joint strength values were between 2.1 and 2.9 kN, resulting of a 724–993% improvement compared to the untreated surfaces. The cyanoacrylate adhesives' bonding reached even higher strengths, it was between 5.0 and 5.6 kN, resulting of a 250–277% increase relative to its untreated surfaces. The measurement results showed that both adhesive joints improved with the wetting. These main effects can be:

The anaerobic adhesive strengths improvement reacts for oxide removal and exposure of active Fe^{2+}, creating efficient curing and stronger bonding.

The cyanoacrylate adhesive strengths improvement reacts for enhanced wetting and polarity.

Comparative Analysis of DC01 and S235

The DC01 steels had a cleaner and more homogenous surface chemistry. During the laser surface modification, the surface achieved hydrophilic activation even at medium laser power levels. While S235 steel containing thicker oxide layer which required higher laser surface energy densities to achieve similar good wetting, but once the activated surface was achieved, its adhesion strength exceeded the DC01 steels behaviour.

Main differences were found during the research in relative strength. Using DC01 the acrylic adhesive strengths improved 8–10 times, and in the cyanoacrylate case by 2.5 times. Using S235 the acrylic adhesive strengths increased by 6–7 times while the cyanoacrylate adhesive improved by around 100 times.

The wetting contact angles and strength results showed that the combined effects of surface activation and adhesive reaction and cure mechanism determine the final level of bonding performance.

DC01 steel showed a more reproducible activation, while S235 showed a wider but more parameter sensitive improvement range. The connection between the chemical nature of the adhesives, the steels surface conditions, and the effect of the surface treatment can be summarized as:

- Anaerobic acrylic adhesive (Loctite 270) showed strength increases, which are primarily happed because of the presence of metallic ions and the removal of the thick oxide layer.
- Cyanoacrylate adhesive (Loctite 496) showed that the adhesion correlates with surface polarity and wetting. When the surface became hydrophilic the adhesion strength reached high values.
- The DC01 steel responds well to laser surface treatment due to its simple oxide structure, and it achieved a good wetting surface activation even using lower laser power levels.
- The S235 steel required higher laser surface energy to break down the oxide layers, but in this case once the surface reached a wetting activated state it achieved exceptionally high adhesion strengths – with the cyanoacrylate adhesive - due to the adhesive strong polar curing response on the S235 surface.

These findings shows that laser surface activation processes can effectively create an improved chemical condition. This method can optimize the connection between the adhesive type and substrate reactivity.

Conclusion

In this study the wettability and adhesive joint strength improvement were investigated using impulse laser induced surface activation on DC01 and S235 steels. Using the surface activation process the surfaces were hydrophilic, this creates a modified chemical condition on the surface compared to the untreated surface, which improves the adhesive bonding process. The main results are the following:

- The laser surface treatment decreased the water contact angle from the original untreated ~73° (DC01) and ~90° (S235) to below 5°. This confirms that hydrophilic surfaces can be created through oxide layer modification, surface carbon removal, and hydroxylation.
- Using different laser surface parameters when the contact angle decreased, the adhesive strength increased in all cases.
- Using anaerobic acrylic adhesive (Loctite 270) the joint strength increased from 0.29 → 2.9 kN on DC01 (which is around 10 times improvement) and 0.57 → 3.9 kN on S235 (which is around 6 times improvement). These improvements can be happed because of the laser created micro-roughness that enhanced both wetting and mechanical interlocking.

– Using cyanoacrylate adhesive (Loctite 496) the adhesive joint strength increased from 2.0 → 5.6 kN on DC01 and 0.06 → 6.1 kN on S235 (which is around 100 times improvement). The strength could be increased because of the surface polarity and moisture-induced polymerization efficiency on hydroxylated, hydrophilic surfaces.
– The laser surface activation method showed effective for two different adhesives and two different steels, demonstrating that its industrial applicability as a clean, repeatable, and primer-free pre-treatment process for structural adhesive bonding.

Author Contributions

Conceptualization, Z.W. and M.B.; methodology, M.B.; validation, M.B., investigation, M.B.; resources, Z.W.; data curation, Z.W.; writing—original draft, M.B.; writing—review and editing, Z.W.; visualization, M.B.; supervision, Z.W.; project administration, Z.W.; funding acquisition, Z.W. "All authors have read and approved the final version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.