



Relationship between the developed interfacial area ratio and the adhesion of the bonded joint

Benjámín Márk Körömi^{a,c}, Zoltán Weltsch^b, Miklós Berczeli^{c,*} 

^a Department of Road and Rail Vehicles, Szechenyi Istvan University, Győr, Hungary

^b Department of Road and Rail Vehicles, Zalaegerszeg Innovation Park, Szechenyi Istvan University, Győr, Hungary

^c Department of Innovative Vehicles and Materials, GAMF Faculty of Engineering and Computer Science, John von Neumann University, Kecskemét, Hungary

ARTICLE INFO

Keywords:

DP600 high-strength steel
Surface micro-structuring
Developed interfacial area ratio
Sdr%
Adhesive
Adhesion
Lap shear strength

ABSTRACT

Bonding technologies have evolved significantly over the past decades, playing a crucial role in the field of joining technologies. To date, however, there is no consensus among research groups as to whether surface texture or surface wettability, or both, affect the strength of bonded joints. Bonded joints, as a bonding technique, are highly dependent on the chemical composition of the adhesive or binder. It is also important to note that the strength and the quality of a bonded joint is greatly influenced by surface adhesion and its related phenomena. From a materials science perspective, surface adhesion is characterised by the level of surface wetting and the total surface energy. In addition, microtopographies and other geometrical features play a key role in bond formation. In this research, the goal is to create controlled microtopographies on DP600 steel surfaces, mainly using femtosecond pulsed laser surface treatment techniques. The ability of adhesives to fill microtopographies specifically, the extent and manner in which micro-scale geometries and structures are filled is also investigated. This allows for the establishment of correlations between the strength of adhesive bonds and the shape characteristics of the microtopography, both in the surface-activated and non-surface-activated states.

Introduction

In recent decades, adhesive bonding has become an increasingly important technique in engineering practice, offering flexible solutions for joining a wide variety of materials. Although its advantages are widely recognized, the underlying factors that influence joint strength are still the subject of active debate. Several studies have emphasized the role of surface texture, others point to surface wettability, and many suggest that their combined effect must be considered in a more integrated manner (da Silva et al., 2018). The chemical composition of the adhesive is undoubtedly a key factor in the bonding process (Chang and Gent, 1981), but this alone cannot explain variations in joint performance. Surface adhesion, including both physical and chemical interactions at the interface, also has a major influence (Ye et al., 2024). These interfacial phenomena are largely governed by the ability of a surface to be wetted and by its total surface energy (Sun et al., 2021). Furthermore, the topographical features of the substrate surface, particularly the presence of microstructured features, can enhance mechanical interlocking and promote stronger adhesion (Ibatan et al., 2015). In this study, special attention is given to the design of

microstructured steel surfaces using femtosecond laser-based processing. The focus is placed on how different surface patterns affect the way adhesives spread into and fill the small scale features, ultimately influencing bond quality (Baumgart et al., 1995). To gain a deeper understanding of the underlying mechanisms, recent research has increasingly focused on how surface structuring impacts adhesion quality in practical applications.

Technologies related to adhesion and bonding have gained significant importance in improving and advancing joining processes across various industries. Surface structuring has gained significant attention as it directly influences the adhesive joint quality through surface energy, wettability, and geometrical features (Ge et al., 2020). One critical parameter for quantifying the surface geometry is the developed interfacial area ratio (Sdr%), which measures the relative increase in the surface area due to micro-structuring (Reitbauer et al., 2021). The Sdr value is defined as the percentage increase in the surface area compared to a perfectly flat reference surface. While the Sdr parameter is less commonly applied in adhesive technology research, it represents a highly relevant metric for evaluating the effects of laser-induced surface treatments on bond strength (Mittal and Lee, 2023). One of the most

* Corresponding author.

E-mail addresses: koromi.benjamin@nje.hu (B.M. Körömi), weltsch.zoltan@sze.hu (Z. Weltsch), berczeli.miklos@nje.hu (M. Berczeli).

<https://doi.org/10.1016/j.jajp.2025.100310>

Available online 9 May 2025

2666-3309/© 2025 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

widespread and effective methods for the fabrication of oriented surface structures is laser surface treatment, which enables the targeted control and modification of topographical characteristics (Lei et al., 2019). An increased interfacial area can enhance mechanical interlocking and adhesion strength, particularly when the adhesive effectively fills the created microtopographies (Jonathan. and David., 2015). However, the relationship between Sdr values and adhesive performance remains underexplored, as highlighted in several international studies. This gap in the literature underscores the necessity of investigating Sdr's role in adhesive bonding processes.

Studies of the effects of surface structuring in different publications. Masaki Omiya and his research group focused their research on increasing the adhesion strength between copper and silver-based polymers using micro- and nanostructures fabricated by femtosecond laser surface treatment. The effects of the surface structures were analyzed by numerical simulations and the adhesion strength was validated by shear tests. In the tests, the optimum ratio between the depth and pitch of the micro-structures was found to be between about 1.5 and 2.5, which provided significant adhesion strength through the so-called "anchor effect". One of the outstanding results of their research is that they achieved >3-fold increase in shear strength with each surface structure compared to the original control surface. Simulation models have shown that the location of the LIPSS structures is of paramount importance in increasing adhesion. For example, when these patterns were created at the tips of micro-structures, a significant improvement in adhesion strength was observed compared to the control surface. In contrast, LIPSS formed in the valleys of the structures were less effective in increasing adhesion. From their research results, it can be concluded that the bond strength can be widely influenced by the optimal choice of the depth and line spacing of the micro-structures, which not only promotes mechanical coupling but also contributes to increased adhesion by improving the chemical interactions on the surface (Omiya et al., 2022). Shangyu Liu and her research team have carried out a detailed study of the effects of femtosecond laser beam-induced micro-structures, with a particular focus on the changes in the depth-surface structure of nickel-based alloys, which are of particular importance for turbine blade surface coating. Scanning electron microscopy (SEM) and confocal laser scanning microscopy (CLSM) were used to investigate the depth changes in the surface structure and the extent of the roughening effects on the micro-structures formed. Using two different temperature-based models, the researchers simulated the heat transfer processes during laser beam treatment and were able to observe the depth of micro-structures formed in the material at different positions under different pulse settings. The simulations determined the variation in the depth of the micro-structures, which was consistent with the experimental results, confirming that the laser scanning speed and focal position have a significant effect on the formation of micro-structures. Their research results suggest that micro-structures formed by femtosecond lasers have a significant effect on surface roughness, which contributes to the improvement of the adhesion and wear resistance properties of the coating. This observation is extremely important for applications of nickel-based alloys requiring extreme temperature resistance, such as in aerospace turbine blades, where the quality of the coatings directly affects the service life and performance of the blades (Liu et al., 2022). Mario Mora et al. have focused their research on increasing the bond strength and improving the thermal conductivity properties between copper surfaces and epoxy adhesive, with particular emphasis on maintaining electrical insulation properties, which is a very important requirement for superconducting coils. For their tests, they used Loctite Stycast 2850FT epoxy adhesive, reinforced with aluminium oxide particles, thus increasing the thermal conductivity of the bond. To alter the surface structure of the copper, laser micro- and nano-patterns were created with the primary aim of increasing the strength of the bonded joints. In the study, the researchers experimented with varying different laser parameters, such as pulse repetition frequency and pulse width, and then analyzed the surface micro-structure using a scanning

electron microscope (SEM), while surface roughness was measured using a confocal laser scanning microscope. The laser surface treatment significantly increased the bond strength, with the maximum shear strength of the laser-structured copper-epoxy bonds reaching 30–32 MPa, which was much higher than the results measured for control surfaces. The researchers also subjected the bonded joints to cyclic thermal stress (–196 °C to 25 °C) and found that the adhesion strength of the laser-structured surfaces hardly changed in response to the stress. Finally, thermal resistance measurements demonstrated that the thermal resistance of copper-epoxy joints depends mainly on the thermal conductivity and thickness of the epoxy material, while the effect of the oxide layer on the copper surface is negligible, especially at room temperature (Mora et al., 2021).

As a result of the literature research, the effect of treatment parameters on the emerging micro-structure needs to be examined using a complex, multi-pronged approach. It is important to consider that changes in micro-structure have a significant effect on the strength of the bonded joints. However, the exact mechanism of these processes is not yet fully understood, and it is also a key question whether different materials and adhesives react differently to the effects of surface treatments. As a result, thorough and detailed studies are needed in each case to better understand the interactions between the different factors and to optimize the system.

Materials and methods

DP600 High-Strength Steel. The material composition of the steel sheet used in this research was analysed with an Oxford Instruments Foundry Master Pro optical emission spectrometer. Before the measurement, the spectrometer was calibrated to ensure optimum performance and resolution. The spectrometer used is capable of accurately determining the values of selected chemical elements within the range of 0.01–0.0001 %. In this present study, DP600 ferrite-martensitic high strength automotive steel was used as the base material for the bonded joints. While DP600 steel is commonly available in a galvanized form, the material employed in this study was specifically selected in an uncoated condition to suit the objectives of the investigation. The material composition determined from spectroscopic analysis of DP600 steel is shown in Table 1 below. The results are expressed in weight percent (wt %).

This type of steel, besides its iron content of 98.5 %, contains additional alloying elements: 0.07 % carbon, 0.185 % silicon, 0.934 % manganese, 0.02 % chromium, 0.0314 % nickel and 0.0043 % vanadium, among other components. The basic characteristic of the steel is the dual fabric structure of ferrite and martensite, which provides both excellent ductility and high strength.

In terms of its use, DP600 steel is particularly popular in automotive applications where high strength and energy absorption are essential factors, such as body panels, door beams and frame structures. The material has a yield strength of 340–370 MPa and tensile strengths of up to 600 MPa. The ductility of DP600 steel allows the use of deep drawing and other forming technologies, which contributes to the production of complex components. The geometry of the specimens for the test was obtained by cutting them with a machine table shear.

Loctite® EA 9466 - 2K epoxy structural adhesive. In the adhesive joints tested in this paper, Loctite® EA 9466 - 2 K epoxy structural adhesive, distributed by Henkel Hungary Ltd., was employed. Loctite® EA 9466 is a tough, industrial-grade, two-component epoxy adhesive

Table 1
Material composition of the steel plate [wt%].

C	Si	Mn	P	S	Cr
0.07	0.185	0.934	0.015	0.0035	0.02
Mo	Ni	V	Ti	Al	Cu
0.002	0.0314	0.0043	0.004	0.04	0.007

developed for the structural bonding of large functional components and modules used in the automotive, electronics and construction industries. The main advantages of Loctite® EA 9466 adhesive include its high strength against peeling, high strength against shear stress and excellent electrical insulation properties. The adhesive is suitable for bonding steel, aluminium, polycarbonate, nylon, wood, GRP and ABS surfaces treated in various ways. The adhesive is cured by a chemical reaction initiated by mixing the two components, with a 2:1 mixing ratio (resin: crosslinking component) being of prime importance. The speed of the curing reaction is influenced by the air temperature in the system/test room. While at 22 °C the bond reaches 100 % of its strength in 72 , at 80 °C it can fully cure in up to 1 hour. Loctite® EA 9466 has excellent resistance to most industrial chemicals, particularly engine oils, fuels and propellants (e.g. petrol), salt mist, acetone and isopropanol, where the bond will retain virtually all its initial strength or even increase over time. However, it has medium/temperature resistance to water/glycol (50/50 wt%) mixtures, condensing moisture and high humidity (98 %). It is extremely important that the substrate surface is clean, dry and free from grease, oil, dust and dirt before bonding. According to the data sheet provided by the manufacturer, the adhesive has an elongation at break of 3 %, a modulus of elasticity of 1718 MPa and a shear strength of 37 MPa for sandblasted steel and 26 MPa for polished aluminium. The bonded joint provides 100 % of its strength at around 20–25 °C, decreasing to 50 % at around 40 °C and further decreasing to 10 % of maximum strength between 60–120 °C.

Coherent Monaco 1035 Ultrashort Pulse Femtosecond Laser. For the laser surface structuring procedures, a Coherent Monaco laser operating in femtosecond pulse mode at a wavelength of 1035 nm was used. The maximum power that can be emitted by this system is 60 W, the pulse length is between 277 and 10,000 femtoseconds, and the frequency range is freely variable between 188 kHz and 50 MHz. The laser beams are guided into the scanning head by means of mirrors, where the laser beam can be directed to the right spot by using movable mirrors. The laser beam is guided by a Scanlab F-theta lens scanning system.

The scanning and surface structuring parameters used in this research were set in the Scanlab programming environment. In the surface structuring process, a power of 24 W, a pulse length of 10 µs, a frequency of 750 kHz, a mark speed of 10 m/s and an energy per pulse of 80 µJ were applied.

Surface Structuring. Within the scope of this study, three different types of laser structured surfaces (type A, B, C) were investigated. For type A, the patterns were formed in an arrangement perpendicular to the direction of the lap shear strength tests. In contrast, the structures of type B were in an arrangement parallel to the direction of the lap shear strength tests. While the type C specimens had a combination of the previous two cases, i.e., a quadrilateral arrangement. In each case, the predetermined Sdr values (100 %, 75 %, 50 %, 25 %) were obtained by purposefully varying the depth of the treatment of the respective type. The specific depth of the structures was adjusted by changing the number of pulse repetitions of the laser treatment. For type A, both the untreated (upper straight surfaces of the structure) and treated parts (valleys) of the surface were 67 ± 2 µm wide. For type B topography, due to the phenomenon of linear polarization, topographies with width values of 79 ± 2 µm (for both laser beam treated and untreated parts) were produced, which differed from those of type A. For type C structures, treated parts with the same orientation as type A and a width of 67 ± 2 µm, as well as untreated parts with a width of 79 ± 2 µm, were produced. While for type B structures, both treated and untreated parts with the same orientation were prepared with a width of 79 ± 2 µm. In the following, the preparation, shape and size characteristics of the given micro-structures are presented as a function of different Sdr values. The laser surface structuring was uniformly applied across the entire bonded area to ensure consistent topographical features and to enable objective evaluation of the effects of varying Sdr% values. However, it is important to note that the regions near the ends of the overlap are particularly critical in terms of joint strength, as stress peaks typically develop in

these zones under shear loading. By treating the entire surface, it is ensured that the high-stress regions also receive adequate surface activation, which is essential for improving adhesion performance in the area most susceptible to failure.

Surface Micro-Structures with 100 % Sdr. The depth of structures on type A surfaces with 100 % Sdr value was 67 ± 2 µm, which was obtained with 620 laser pulse repetitions, while for type B surface, 850 pulse repetitions were used to obtain a depth of 79 ± 2 µm. On the square-grid structured (C type) surfaces, $360 + 40$ pulse repetitions (horizontal direction) and $441 + 20$ pulse repetitions (vertical direction) were used to achieve an average depth of 44 ± 3 µm (Fig. 1). Due to the more complex geometry and the perpendicular treatments, a more uneven topography was observed for the square mesh surfaces. For this reason, a smaller number of pulse repetitions (+40 and +20) was introduced at the end of the treatment, because of their smoothing effect, resulting in a smoother and more homogeneous structure.

Surface Micro-Structures with 75 % Sdr. To produce surfaces with 75 % Sdr, the number of laser beam pulse repetitions described in the previous chapter was reduced. As a result, the depth of type A structures was reduced to 52 ± 2 µm, type B to 62 ± 2 µm and type C to 33 ± 3 µm. In case A, 465 pulse repetitions were used, in case B, 720 and in case C, $260 + 40$ and $326 + 20$ pulse repetitions were used (Fig. 2).

Surface Micro-Structures with 50 % Sdr. To achieve 50 % Sdr values, while type A pattern was designed with 310 pulse repetitions (36 ± 2 µm depth), type B with 425 pulse repetitions (36 ± 2 µm depth) and type C with $160 + 40$ and $211 + 20$ repetitions (22 ± 3 µm depth). Fig. 3. illustrates the structures designed with the parameters described in this chapter.

Surface Micro-Structures with 25 % Sdr. The depth of type A with 25 % Sdr was 18 ± 2 µm, type B with 18 ± 2 µm and type C with 11 ± 3 µm (Fig. 4.). In case A 155-, in case B 213- and in case C $60 + 40$ - and $95 + 20$ pulse repetitions were used.

Control Surface with 6 % Sdr. For the control surfaces, the specimens were cleaned with alcohol, after which the necessary examinations and tests were carried out on their surfaces, and then the bonded specimens were prepared. Surface examination of the control specimens showed an average Sdr=6 % and a surface roughness of <2 µm due to the manufacturing process (Fig. 5).

Olympus LEXT OLS5000 confocal laser scanning microscope. The Olympus LEXT OLS5000 confocal laser scanning microscope is a materials science microscope capable of high-resolution, high-speed imaging. It can also perform non-contact 3D inspections and measurements with an accuracy of up to 10 nanometres. It is equipped with two light sources, a white light source for the collection of colour data and a diode laser light source operating at 405 nm wavelength for the recording of height and other dimensions and features. The microscope can be used to take various images and surface measurements at magnifications of 5X, 10X, 20X, 50X, 100X. In this research, the Olympus LEXT OLS5000 confocal laser scanning microscope was used to obtain measurements and images of microstructures formed on the DP600 steel surface, and to investigate the effects of laser beam parameters, all at 20X magnification. The profile method type measurement was performed according to ISO 21920-2:2021 (ISO 21920-2 2021) and the area measurement according to ISO 25178-2 (ISO 25178-2 2021). The tests were repeated three times and performed on different areas of the surfaces.

Adhesive Technology. The samples prepared for the single overlapped shear test in this research were prepared in accordance with the ISO 4587 standard (ISO 4587-3 2003). In all cases, the bonding procedure was carried out by first alcohol distillation and then laser structuring of the specimens. After the structuring, the specimens were cleaned again in an ultrasonic cleaner to ensure that no contaminant particles remained in the structure during the surface treatment and to achieve the desired geometry as accurately as possible. Subsequently, 0.1 g of Loctite 9466 2 K adhesive was applied to the area to be bonded. The standard specifies the exact size of the specimens subjected to the

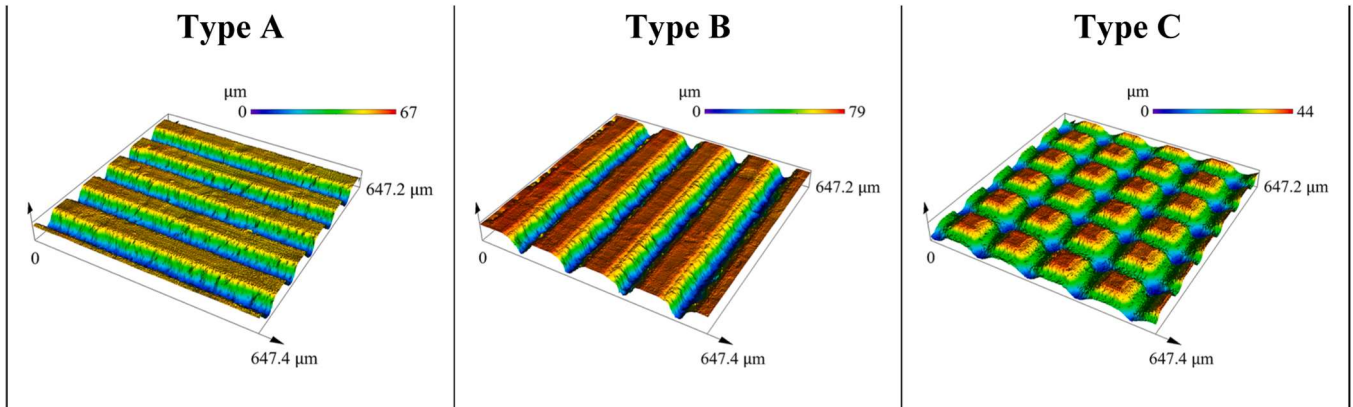


Fig. 1. Three-dimensional laser-scanned surface microtopography on steel sheets with 100% Sdr adhesion surface according to the area method of ISO 25178.

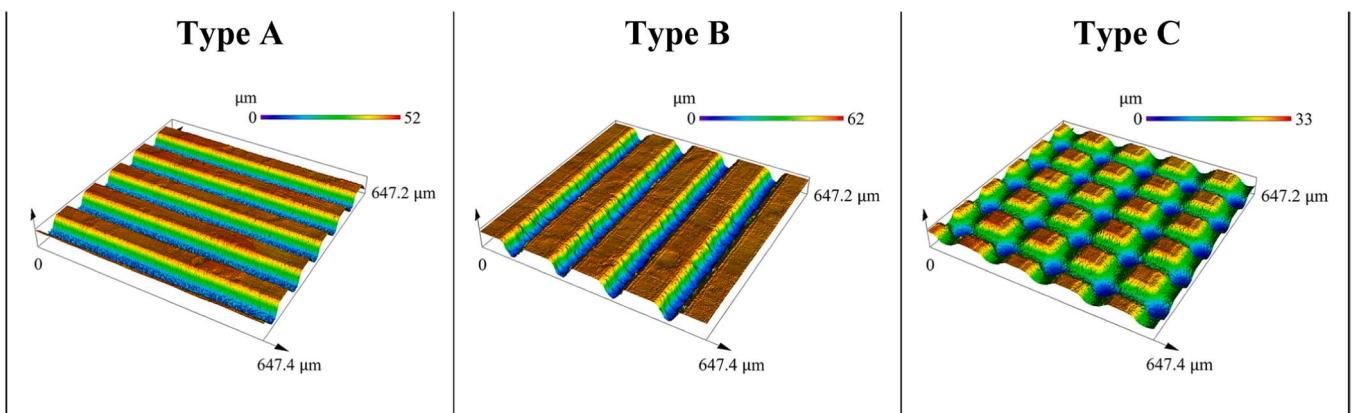


Fig. 2. Three-dimensional laser-scanned surface microtopography on steel sheets with 75% Sdr adhesion surface according to the area method of ISO 25178.

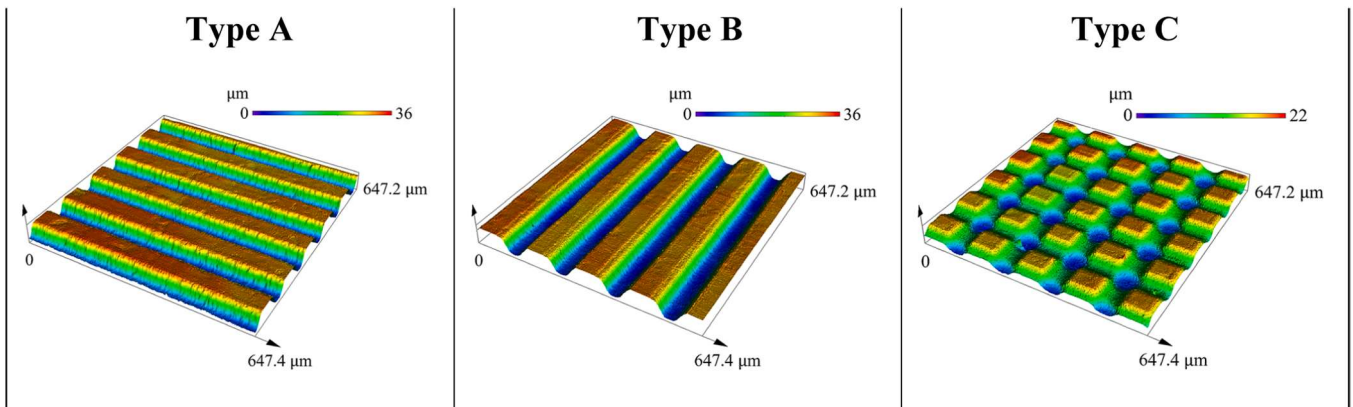


Fig. 3. Three-dimensional laser-scanned surface microtopography on steel sheets with 50% Sdr adhesion surface according to the area method of ISO 25178.

lap shear test and the size of the overlapped bonded area, which requires the overlapped bonded area to be 25 ± 0.25 mm wide and 12.5 ± 0.25 mm long (Fig. 6). The size of the bonded areas prepared according to the standard is ≈ 312.5 mm². In this research, the bonded joints were prepared using $a \approx 0$ mm bonding gap as recommended by the adhesive manufacturer, with prolonged clamping pressure applied during the curing process.

Lap Shear Test of the Bonded Joints. The bonded joints were lap shear tested using an INSTRON 5900R 4482 universal testing machine. The specimens were gripped between clamping heads during the lap shear tests, and intermediate pieces were used during the clamping to

ensure uniaxial loading, and the required standard lap shear strength tests were performed. For the tests, a lap shear test speed of 10 mm/min was applied. The standard also specifies a failure time for the specimens of 65 ± 20 s. Five samples were used for each parameter tested. Fig. 7 shows the arrangement of the tests.

Results

Lap Shear strength of bonded joints as a function of the different oriented micro-structures. In the course of investigating the lap shear strength of adhesive joints, surfaces treated with different surface

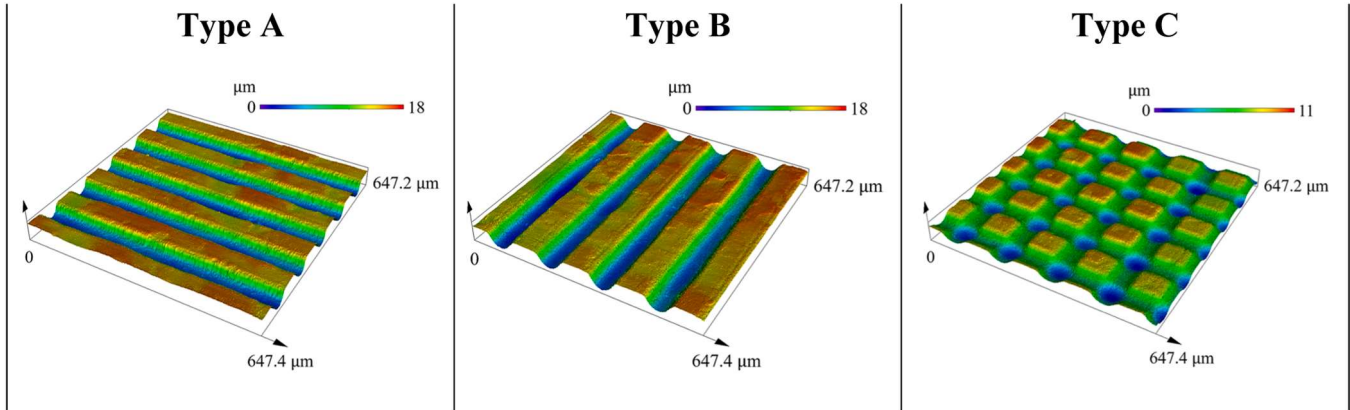


Fig. 4. Three-dimensional laser-scanned surface microtopography on steel sheets with 25% Sdr adhesion surface according to the area method of ISO 25178.

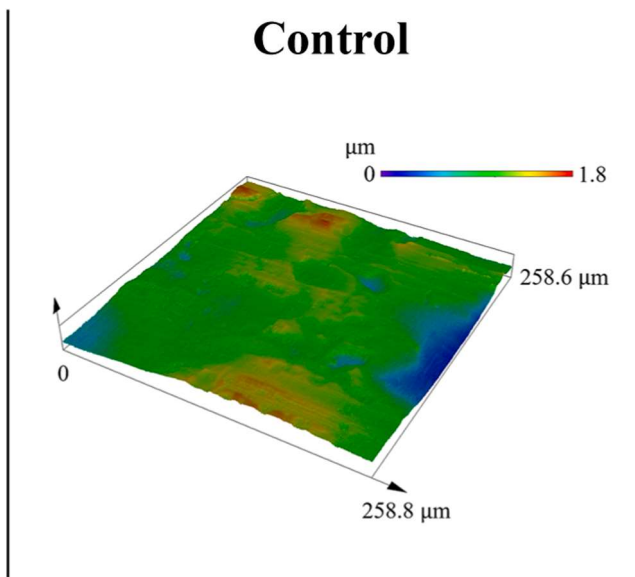


Fig. 5. Control surface with 6% Sdr.

structuring methods, as well as the resulting lap shear strength characteristics of the adhesive joints manufactured using these surfaces, are presented. The values of the columns in the diagrams are plotted as a function of the surface texturing procedures on the horizontal axis and

the lap shear strengths applied on the vertical axis. In all cases, the lap shear strength values shown are in MPa.

In presenting the research results, the lap shear strength of bonded joints will be examined from two different approaches. On the one hand, from the approach used in the scientific community, where the lap shear strength is calculated according to Eq. (1). For the lap shear strength values calculated from the nominal bonded area, the lap shear strength of the bonded joints was determined as the shear force divided by the shear cross-sectional area. The lap shear strength (τ) was calculated using the nominal bonded area ($A = 12.5 \text{ mm} \times 25 \text{ mm}$), as commonly applied in adhesion testing according to ISO 4587. This method assumes uniform stress distribution across the overlap area and is widely used in both scientific literature and industrial practice. Calculation of lap shear strengths using the nominal bonded area (Eq. (1))

$$\tau = \frac{F}{A} = \frac{F}{a * b} [\text{MPa}] \quad (1)$$

where τ is the lap shear strength [MPa], F is the maximum shear force [N], A is the sheared cross-sectional area [mm^2], a is the length of the shorter side of the bonded area ($a = 12.5 \text{ mm}$), b is the length of the longer side of the bonded area ($b = 25 \text{ mm}$).

On the other hand, a scientific suggestion was made that the strength of the joints should be determined by considering the size of the actual bonded areas in order to establish more precise, scientific relationships. The theoretical background of the hypothesis was based on the assumption that surface treatments involving material removal affect the size of the bonded areas. For most surface treatments, the size of this area increase is extremely difficult or impossible to determine. On the

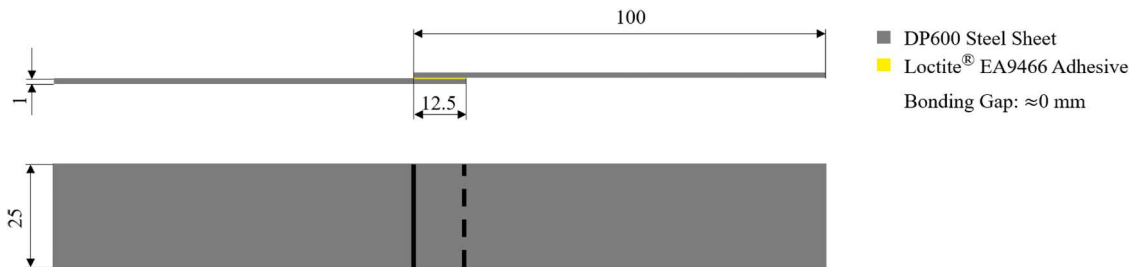


Fig. 6. Geometry of tensile test specimens and adhesive.



Fig. 7. Illustration of high strength adhesive lap shear testing on steel sheets.

other hand, Eq. (2) becomes particularly applicable in cases where surface treatments result in highly regular and repeatable micro-structures across the bonded interface. When controlled surface features are introduced, such as those generated by femtosecond laser structuring, precise surface topography measurements can be conducted on a small, representative section of the surface using confocal microscopy or similar methods. Due to the periodic nature of the structures, the measured developed interfacial area ratio (Sdr%) from this subsection can be considered valid for the entire bonded area. Eq. (2) is intended to reflect a more physically accurate representation of lap shear strength by accounting for the actual developed bonding surface, rather than the nominal flat area. The developed interfacial area ratio (Sdr%) quantifies the relative increase in surface area caused by micro-structuring, compared to an ideally flat surface. In laser-structured surfaces, the adhesive does not bond to a flat plane but rather to a three-dimensional microtopography with grooves and ridges, increasing the real contact area significantly. By dividing the maximum shear force not by the nominal overlap area but by the real bonded area (i.e., nominal area multiplied by $1 + \text{Sdr\%}/100$), a more accurate representation of the actual stress distribution and interface behavior is obtained. This aspect is particularly important when evaluating the efficiency of surface treatments, as high Sdr values increase the surface area, but not necessarily result in a proportional increase in adhesion strength, as demonstrated by the results. Therefore, using the real bonded area provides a more local insight into the effectiveness of micro-structuring. The lap shear strength values were determined based on the real bonded area by dividing the maximum shear force by the product of the nominal bonded area and the relative surface area increase. This approach allows us to account for the actual effective bonded surface, considering the increased surface area resulting from the surface treatment.

Calculating lap shear strengths using the value of the real bonded area (Eq. (2))

$$\tau = \frac{F}{A * \text{Sdr\%}} = \frac{F}{(a * b) * \text{Sdr\%}} \text{ [MPa]} \quad (2)$$

where τ is the lap shear strength [MPa], F is the maximum shear force [N], A is the sheared cross-sectional area [mm²], a is the length of the shorter side of the bonded area ($a = 12.5$ mm), b is the length of the longer side of the bonded area ($b = 25$ mm), $\text{Sdr\%}$ is the relative surface area increase.

In the adhesive joints investigated, a 0 mm adhesive bond line thickness was targeted. This was achieved by applying continuous clamping to the bonded specimens during the curing process of the two-component epoxy adhesive. Consequently, an adhesive layer thickness of approximately 60–80 μm was obtained. During mechanical testing, adhesive failure was predominantly observed at the upper regions of the microstructured surface, while in certain cases, cohesive failure was detected within the grooves of the microstructure. The observed failure mode was found to be dependent on the Sdr%.

In cases where cohesive failure occurs and the geometry of the microstructure does not exert a significant influence, it is considered that the bonded joint fails along a theoretical $a*b$ surface. The patterned nature of the microstructure, the actual fracture surface of the adhesive is increased to some extent relative to the nominal $a*b$ area, and failure is not confined to an idealized planar interface. The applicability of the formula is justified scientifically and practically in cases where the thin, high-strength, and low-ductility adhesive layer is incapable of cohesive failure due to its limited thickness, resulting instead in adhesive detachment from the substrate. Under these specific conditions, Eq. (2) can be applied without restriction. While Eq. (1) is recognized as being more relevant from the standpoint of engineering design due to its direct relation to measurable force and stress values the purpose of the present study was to explore adhesion mechanisms within geometrically structured interfaces. The application of Eq. (2) was found to exhibit a more coherent and scientifically justified correlation with the Sdr%,

particularly when considering the patterned microgeometries.

In this work, the effectiveness of adhesive filling in the engineered, directionally structured micro-structures was also investigated. Following the lap shear strength tests, images of the bonded surfaces from failed specimens were analyzed, captured using an Olympus LEXT OLS5000 confocal laser scanning microscope. Based on these observations, it was estimated that the micro-structures were likely filled effectively by the adhesive. To confirm full penetration, further targeted investigations are needed. In the next phase, scanning electron microscopy (SEM) analysis of the bonded joints is planned to be conducted, and the wettability of the micro-structure walls is to be measured, which is expected to provide clearer insights into the adhesive spreading and filling properties.

From these two different approaches, the lap shear strength results for bonded joints are presented.

Lap Shear strength results as a function of the nominal bonded area value. In all the tests carried out, the bonded joints made from control, alcohol-cleaned, untreated surfaces gave the lowest lap shear strength values. The lap shear strength values presented in Fig. 8 were determined in accordance with the calculation method outlined in Eq. (1). As illustrated in Fig. 8 below, the average lap shear strength of the control surface specimens was 5.2 MPa.

For the surfaces with structure A, specimens with Sdr=100 % were found to provide one of the highest strength results, with an average of 30.8 MPa. The lap shear strength value of bonded joints formed between surfaces with 75 % Sdr was reduced compared to the results of specimens with 100 % Sdr. In this case the lap shear strength of the bonded joints was 25 MPa. In contrast, bonded specimens with 50 % Sdr resulted in increasing strength values (27.6 MPa) despite the smaller relative surface area. Specimens with 25 % relative surface area, on the other hand, again showed a decreasing trend, with an average strength value of 24.5 MPa.

For the surfaces formed with structure B, specimens with Sdr=100 % were found to result in the highest strength values, with an average lap shear strength of 31.8 MPa. The 75 % Sdr resulted in a deterioration of the lap shear strength of the bonded joints. This resulted in average values of 28.1 MPa. However, at Sdr=50 %, in contrast to the trend of type A, strength values decreased further (25.8 MPa), presumably due to the smaller relative surface area and the change in orientation of the structures. Conversely, the Sdr=25 % samples resulted in a slight increase in strength values (27.8 MPa).

Also, among the strength values of the surfaces with structure C, it was observed that the Sdr value of 100 % resulted in the highest lap shear strength, which in this case was 28.4 MPa. Subsequently, a similar trend was observed for the surfaces with type A structure. That is, the specimens with Sdr=75 % showed a reduced strength (25.9 MPa) compared to the values with Sdr=100 %. However, the strength of bonded joints made from surfaces with 50 % Sdr showed a small but significant improvement compared to the strength results of specimens with both 75 % and 25 % Sdr, which in this case resulted in an average lap shear strength of 27.5 MPa (Fig. 8).

Lap Shear strength results as a function of the real bonded area value. If the strength values are calculated and plotted considering the amount of surface growth due to structuring, the results described in the previous section are radically different. The lap shear strength values calculated based on the methodology described in Eq. (2) are presented in Fig. 9. As illustrated in Fig. 9 below, the control and base surface had a small relative surface area increase and consequently its strength value did not change significantly (4.9 MPa).

However, for surfaces A, B and C, a striking change occurred after accounting for the relative surface area increase, as a clear trend in lap shear strength values is observed (Fig. 9).

The lap shear strength of bonded joints made from surfaces with structure type A and 100 % Sdr resulted in the lowest average values of 15.4 MPa. The specimens with Sdr=75 %, despite the smaller relative surface area, resulted in higher lap shear strength (16.2 MPa) when

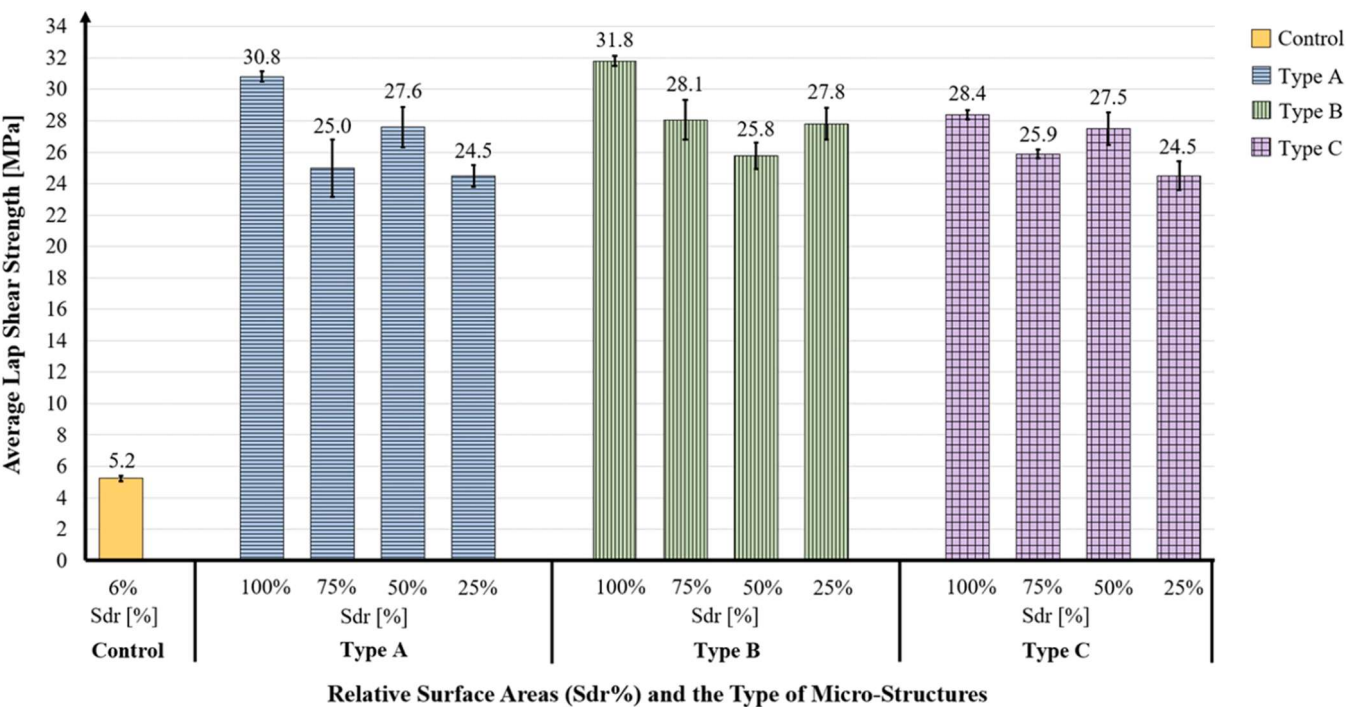


Fig. 8. Illustration of lap shear strength of bonded joints as a function of surface structuring procedures (for calculation with the nominal bonded area).

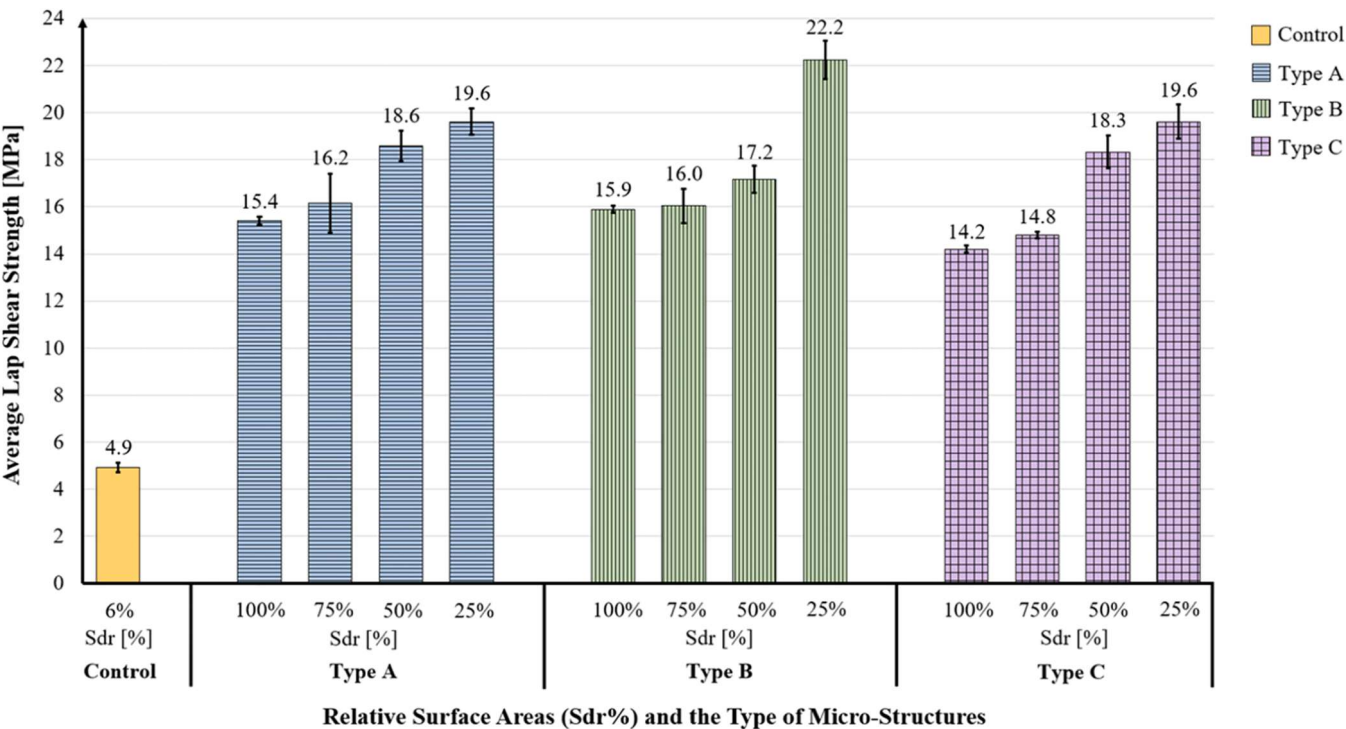


Fig. 9. Illustration of lap shear strength of bonded joints as a function of surface structuring procedures (for calculation with the real bonded area).

calculated with the real bonding area. This increasing trend was also observed for specimens with Sdr=50 % and Sdr=25 %. The highest strength of 19.6 MPa was obtained for the specimens with the lowest relative surface area increase.

For the surfaces with structure B, the specimens with Sdr=100 % resulted in an average lap shear strength of 15.9 MPa. The 75 % Sdr resulted in a negligible increase in the lap shear strength of the bonded joints. This resulted in average values of 16 MPa. When 50 % Sdr was

applied, the strength values increased further, in this case to 17.2 MPa. While the highest results reported in this chapter were provided by specimens with 25 % Sdr with an average lap shear strength of 22.2 MPa.

It is also observed that the strength values of the surfaces with structure C were found that the 100 % Sdr value resulted in the lowest lap shear strength, which in this case was 14.2 MPa. Subsequently, a similar trend was observed for the surfaces with structure type A and B.

That is, the specimens with $Sdr=75\%$ showed increasing strength (14.8 MPa) compared to the values with $Sdr=100\%$. However, the strength of bonded joints made from surfaces with Sdr values of 25 % continued to increase compared to the strength results of specimens with both Sdr values of 50 % and 75 %, resulting in an average lap shear strength of 19.6 MPa.

Failure modes of adhesive joints. Based on the macroscopic images taken after lap shear testing, distinct fracture modes were identified across the various surface structuring conditions. These fracture characteristics provide essential insight into the interfacial behavior and mechanical performance of the adhesive joints, particularly in relation to the influence of laser-induced surface topographies and their quantification via the developed interfacial area ratio ($Sdr\%$). The results can

be seen in Fig. 10.

In the case of the Control type specimens ($Sdr = 6\%$), which were not laser surface treated, the fracture surfaces showed adhesive failure mode. This was evident from the complete detachment of the adhesive layer from the steel surface, with most of the adhesive layer remaining intact on the opposing substrate. Such failure mode indicates weak interfacial bonding, likely due to the lack of surface preparation. The lack of mechanical interlocking, owing to the smooth surface morphology, further contributed to the low bond strength observed in these specimens, which averaged 5.2 MPa. This represents the baseline performance of the adhesive-substrate system without any surface activation.

The laser-structured specimens revealed a transition from adhesive to cohesive and mixed failures mode, depending on the level of surface

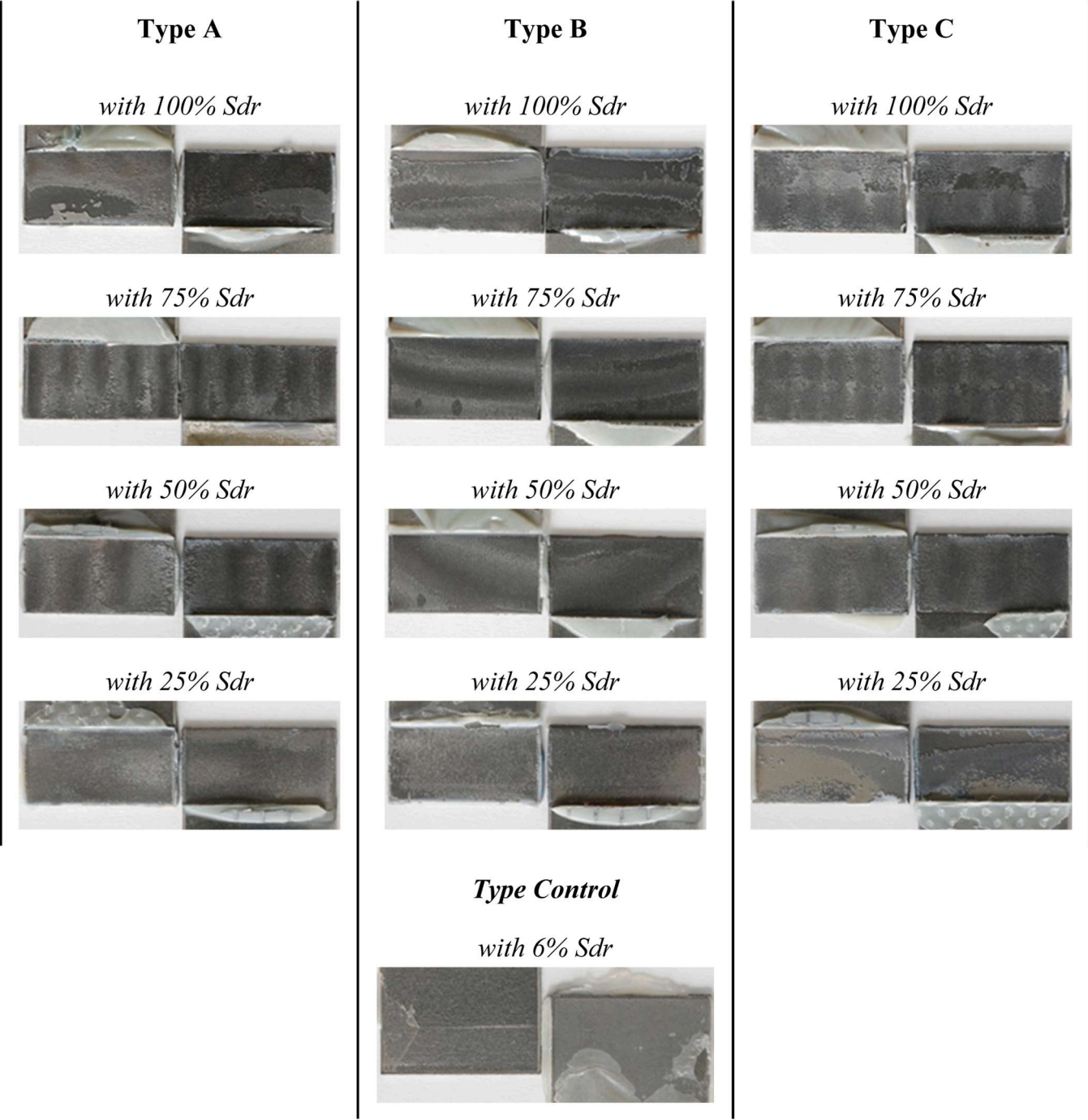


Fig. 10. Failure modes of adhesive joints depending on surface structuring procedures.

development. In specimens treated with the highest level of structuring ($Sdr = 100\%$), mixed-mode failures were most commonly observed. In these cases, adhesive residue was present on both substrates, suggesting failure occurred partly within the adhesive and partly at the interface. This indicates improved adhesion, where interfacial strength approached or exceeded the cohesive strength of the adhesive. For these specimens, the lap shear strength based on the nominal area significantly increased, reaching approximately 30.8 MPa for type A, 31.8 MPa for type B, and 28.4 MPa for type C. However, when calculated using the real bonded area (considering the $Sdr\%$), the normalized strength values were more moderate ($\sim 15\text{--}16$ MPa), suggesting that the performance gain does not scale linearly with the increase in surface area, likely due to incomplete adhesive penetration into deep or complex features.

Specimens with intermediate surface development ($Sdr = 50\%$ and $Sdr = 25\%$) frequently showed cohesive failure. In these cases, the adhesive fractured within its own volume, with large portions remaining firmly attached to both surfaces. This fracture behavior reflects a highly favorable adhesive-substrate interaction. The surface structuring was sufficient to ensure anchoring. Notably, specimens with $Sdr = 25\%$ (particularly in type B orientation) achieved the highest normalized lap shear strength when calculated based on the real bonded area, reaching values up to 22.2 MPa, despite the smaller surface increase. This suggests that optimized micro-structuring can outperform more aggressive surface modifications.

In the case of the square-patterned surfaces (Type C), mixed and cohesive failures were also dominant, particularly at $Sdr = 50\%$ and 25% . The increased geometrical complexity due to intersecting laser paths in orthogonal directions appears to have enhanced the mechanical anchoring effect of the adhesive, especially at feature intersections. These specimens reached nominal lap shear strength values of 27.5 MPa ($Sdr = 50\%$) and 27.8 MPa ($Sdr = 25\%$), which, when normalized, again highlighted that lower $Sdr\%$ values may offer more efficient performance gains.

Conclusion

This study systematically investigated the relationship between femtosecond laser created micro-structures quantified by the developed interfacial area ratio ($Sdr\%$) and the lap shear strength of adhesive joints on DP600 high-strength steel. Three distinct structuring orientations (A, B, C) and four controlled $Sdr\%$ levels (100 %, 75 %, 50 %, 25 %) were applied using femtosecond laser technology, resulting in a comprehensive dataset covering both geometric and mechanical aspects of the bonding process.

Two evaluation methods were employed: one based on the nominal bonded area, and another incorporating the real, developed surface area ($Sdr\%$ -based). This dual approach enabled a deeper understanding of how surface geometry influences joint performance. The results led to the identification of several key findings:

- The lap shear strength increased significantly with surface structuring when calculated using the nominal bonded area, rising from 5.2 MPa (control, $Sdr = 6\%$) to over 31 MPa (structured surfaces, $Sdr = 100\%$).
- However, when normalized to the real bonded area, lower $Sdr\%$ values (e.g., 25 %) consistently outperformed higher ones, achieving the highest strength of 22.2 MPa, highlighting that excessive surface enlargement does not linearly translate to strength gain.
- The dominant failure modes transitioned from adhesive ($Sdr = 6\%$) to mixed and cohesive ($Sdr = 25\text{--}100\%$), reflecting stronger interfacial bonding due to surface structuring.
- The most efficient bond performance was achieved with moderate surface structuring ($Sdr = 25\%$) in parallel orientation (Type B),

suggesting an optimal balance between adhesive penetration, mechanical interlocking, and real contact area.

These findings confirm that while increased surface area improves mechanical anchoring, the most effective enhancement in bond strength arises from optimized surface geometry rather than maximal structuring. This study contributes a novel framework for correlating surface topography (via $Sdr\%$) with adhesion performance and provides a foundation for future work focusing on adhesive penetration, wetting mechanisms and localized structuring strategies.

CRediT authorship contribution statement

Benjámín Márk Körömi: Writing – original draft, Validation, Investigation. **Zoltán Weltsch:** Writing – original draft, Visualization, Supervision, Resources, Methodology, Conceptualization. **Miklós Berczeli:** Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

- Baumgart, P., Krajnovich, D.J., Nguyen, T.A., Tam, A.C., 1995. A new laser texturing technique for high performance magnetic disk drives. *IEEE Trans. Magn.* 31, 2946–2951.
- Chang, R.J., Gent, A.N., 1981. Effect of interfacial bonding on the strength of adhesion of elastomers. I. Self-adhesion. *J. Polymer Sci.* 19, 1619–1633.
- da Silva, L.F.M., Ochsner, A., Adams, R.D., 2018. *Handbook of Adhesion Technology*, 2nd ed. Springer International Publishing, Cham.
- Ge, P., Wang, S., Zhang, J., Yang, B., 2020. Micro-/nanostructures meet anisotropic wetting: from preparation methods to applications. *Mater. Horiz.* 7, 2566–2595.
- Ibáñez, T., Uddin, M.S., Chowdhury, M.A.K., 2015. Recent development on surface texturing in enhancing tribological performance of bearing sliders. *Surf. Coat. Technol.* 272, 102–120.
- ISO 21920-2: Geometrical product specifications (GPS) - surface texture: profile - part 2: terms, definitions and surface texture parameters, (2021).
- ISO 25178-2: Geometrical product specifications (GPS) - surface texture: areal - part 2: terms, definitions and surface texture parameters, (2021).
- ISO 4587-3: Adhesives - determination of tensile lap-shear strength of rigid-to-rigid bonded assemblies, (2003).
- Jonathan, R.L., David, W., 2015. *Laser Surface Engineering: Processes and Applications*, 1st ed. Woodhead Publishing, Cambridge.
- Lei, Z., Tian, Z., Chen, X., Chen, Y., Bi, J., Wu, S., Sun, H., 2019. Large spot diameter nanosecond laser treatment of aluminum alloy sheets for high-speed superhydrophobic hierarchical micro- and nanostructured surface preparation. *Surf. Coat. Technol.* 361, 249–254.
- Liu, S., Zhang, Z., Yang, Z., Wang, C., 2022. Femtosecond laser-induced evolution of surface micro-structure in depth direction of nickel-based alloy. *Appl. Sci.* 12, 8464.
- Mittal, K.L., Lee, K.W., 2023. *Polymer Surfaces and Interfaces: Characterization, Modification and Application*, 1st ed. CRC Press, London.
- Mora, M., Amaveda, H., Porta-velilla, L., de la Fuente, G.F., Martínez, E., Angurel, L.A., 2021. Improved copper-Epoxy adhesion by laser micro- and nano-structuring of copper surface for thermal applications. *Polymers (Basel)* 13, 1721.
- Omiya, M., Nakajima, A., Yan, J., 2022. Design and fabrication of micro and nano surface structures for enhancing metal-polymer adhesion using femtosecond laser treatment. *Mater. Des.* 224, 111349.
- Reitbauer, J., Harrer, F., Eckhart, R., Bauer, W., 2021. Focus variation technology as a tool for tissue surface characterization. *Cellulose* 28, 6813–6827.
- Sun, X., Wang, K., Fan, Z., Wang, R., Mei, X., Lu, Y., 2021. Regulation of hydrophobicity on yttria stabilized zirconia surface by femtosecond laser. *Ceram. Int.* 47, 9264–9272.
- Ye, M., Sun, J., Chen, Z., Tao, W., Lian, Y., Yang, Z., 2024. Controlling the morphologies of femtosecond laser-induced periodic surface structure on silicon by combining deep learning with energy deposition model. *Mater. Des.* 242, 113021.