DEVELOPMENT OF THE BONDING TECHNOLOGY OF MODERN AUTOMOTIVE MATERIALS WITH ENVIRONMENTALLY FRIENDLY SOLUTIONS

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Resume

The significance of bonding technology for modern vehicle structural materials is increasingly acknowledged, driven by the adoption of new materials to reduce weight. This is important not only for quality and economic reasons but to address environmental pollution, as well. Traditional joining methods like riveting, screwing, welding, and brazing, are often unsuitable or limited for modern materials. Soldering, an economical and almost waste-free technology, is becoming more widespread. Through optimization, it achieves a strong, durable bond. There is a potential to favourably alter interface properties, including using high energy density surface treatments. Research showed that the laser surface treatment of high-strength steel sheets could improve the mechanical properties of soldered joints.

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1 Introduction

Today, steel continues to be predominantly used in vehicle production, primarily because it is one of the most readily available raw materials, rendering it more cost-effective than other metals with similar properties. Its significant advantage lies in the ability to modify its properties within wide limits at relatively low costs. Furthermore, steel can be recycled without any loss of quality. The only drawback is its heavy weight. This feature is causing more and more problems nowadays, because the environmental protection regulations are becoming increasingly strict. To reduce consumption and emissions, the approach involves either incorporating metals that are lighter but more expensive, such as aluminum-magnesium alloys, or adopting the high-strength steels capable of satisfying strength requirements with thinner sheet thicknesses. Steel or aluminum plates of lower basic strength are used in energy-absorbing places, but high-strength steel is used in places important for safety. Such places are the roof of the car, the A- and B-pillars and the doors, and in certain places, such as the doors, they can also be supplemented with super high-strength steel. With these steels, it is possible to increase safety and still achieve weight reduction [1]. To be able to connect these steels of different strengths problem-free, it is necessary to ensure the appropriate joining technology and the factors affecting it. In bonding technology, the surface of materials being joined and characteristics of interfaces represent one of the most crucial aspects [2-4].

Vehicle weight reduction is a critical task for lowering consumption. Thinner yet high-strength steel plates offer a viable solution for achieving this weight reduction. It is advisable to design the connection of these plates in such a way that it does not significantly increase the weight of a vehicle. It is possible to improve bonding technologies with surface treatment technologies. Laser surface treatment with a high energy density affects the interfacial energy of the treated surface, thus its wetting ability, which plays an important role in the creation of adhesive bonds [5-7].

The core principle of laser surface treatment involves inducing stresses on the material's outer surface that are crucial for stress management. The primary objectives include enhancing the surface's strength and load-bearing capacity, establishing more favourable friction conditions, improving wear resistance, optimizing residual stresses to boost fatigue resistance, and enhancing the corrosion resistance. Laser treatment cannot be economically used for mass property modification, however, it can be used for very precise surface treatments, when it is important to change the properties of the raw material only on the surface layer. Utilizing this method allows for the alteration of the surface oxide layer, the interfacial energy, and creation of a surface microstructure that influences wetting. The extent to which the laser beam is absorbed by the material significantly dictates its applicability for various tasks. To enhance absorption, the surface may be coated with graphite spray. The interaction between the laser beam and the material is basically determined by the following technological parameters [8-10]:

- Laser power [W]
- Wavelength [nm]
- Beam shape, size [mm]
- The nature of the intensity distribution within the irradiated area (TEMij)
- Scanning (forward) speed [m/s].

Hao et al. utilized CO_2 laser surface treatment on corrosion-resistant steel, resulting in nearly a doubling of the O_2 concentration in the steel's interfacial layer and a 10 % increase in surface energy. [1].

Khadka et al. team applied a Nd:YAG laser treatment to a magnesium alloy, with the effects assessed using distilled water. The treatment led to a decrease in the contact angle of distilled water droplets on the surface from 81° to 41°, marking a significant enhancement in wetting [11].

Rotella et al. conducted treatments on DP500 high-strength and AISI 304 corrosion-resistant steel using a wire laser, aiming to improve wetting and thereby enhance the bonding strength. The investigation also covered changes in surface roughness, reporting a notable improvement in the wetting properties of both steels, alongside an increase in surface roughness [12].

Bonds are categorized into dissolvable and non-dissolvable types. If a bond can be removed without destruction with some tool or aid, then the given bond type is classified as a dissolvable bond; however, if the bond can only be removed by destruction, it is classified as a non-dissolvable bond. Dissolvable joint technologies include, for example, rib joints, screw joints and latch joints. The non-dissolvable ones include riveting, welding, soldering and gluing. The solid joints fall into both categories, as their classification as dissolvable or non-dissolvable depends on the extent of part overlap and the assembly technology used, determining whether such joints can be separated without causing destruction.

In the present work, soft soldering is preferred because it is one of the possible joining technologies for joining high-strength steels. Riveting and screwing would also be a good technology, but if the goal is to reduce the weight of vehicles, these fastening methods are not the solution, because those fasteners increase the weight of vehicles. Welding and brazing do not greatly increase the weight of a vehicle, but with these technologies, a melt is formed, which can change the fabric structure of the raw material or even deform it due to the high heat input [13].

Soldering is a widely used joining technology nowadays. The benefit lies in the ability to form a soft-soldered joint at temperatures low enough to preserve the fabric structure of the base material, resulting in minimal deformation. The quality of the joint depends largely on the wetting of the solder. By improving the wetting, the strength of the bond can be further increased.

Drawing from literature data and existing knowledge, it is posited that laser surface treatment on steel material can effectively alter the oxide layer, thereby enhancing the wetting properties and increasing the strength of soft-soldered joints. In the course of the research, the changes in interfacial energy, resulting from the CO_2 laser surface treatment, and its impact on soft-soldered joints are thoroughly investigated.

2 Materials and methods

The DP600 type steel was selected for the tests because of its common application in vehicle

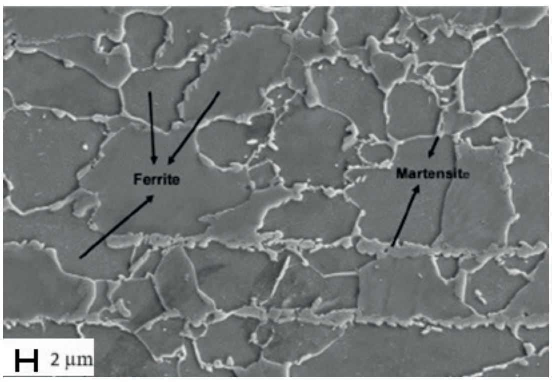

***Figure 1** Metallographic image of DP600 steel [15]*

manufacturing. The numbering of DP steels indicates the tensile strength. Dual phase steels consist of islands of hard martensite embedded in soft, malleable ferrite, the amount of which is usually 10-40%, depending on the desired mechanical properties (Figure 1) [14].

During the series of experiments, a cold-rolled 25 x 55 mm DP600 steel plates of a thickness of 1 mm were used. The plates were cut in such a way that their longer sides were parallel to the rolling direction. The results of the research can be impaired by a contaminated surface, so the surfaces were cleaned on-site with 96% methanol, directly before the treatment, which was applied to the surface with a sterile cotton swab and wiped off. The plate was then dried immediately after cleaning using a hot air dryer.

During the laser surface treatment, a laser with a CO_2 source was used, specifically a Unisonic 900 type engraving laser, capable of a maximum power of 100 W. Furthermore, the treatment parameters were determined experimentally. In this case, the focus diameter was fixed at 0.1 mm, and the increment was also set to the same amount.

During the laser beam surface treatment, the variable parameters were power and scanning speed, the set power values were: 35 W, 50 W, 65 W and 80 W, while the speed values were 25 mm/s, 37 mm/s, 48 mm/s and 60 mm/s. With this set of parameters, the extreme values of the machine's application range are covered (Figure 2).

The wetting was investigated using the resting drop method. The temperature in the measuring room was 20 ± 1°C. The treated steel plate was placed on the stage, 5 µl of distilled water was drawn into the micropipette, and it was then positioned in the pipette holder on the stand. The water drop was gently squeezed to prevent dripping, causing it to hang at the end of the pipette tip. Subsequently, the plate, along with the stage, was raised to bring the water drop into contact with the plate's surface, resulting in the water drop jumping onto the plate. The stage was then lowered to position the drop at the center of the camera's view. To capture a photograph, the focus was adjusted using the micrometers on the microscope stage. When the image appeared sharp on the camera, the drop was photographed using a remote control with a 2-second delay to reduce errors caused by camera shake. These processes were also carried out using ethylene glycol, and the photos were saved in separate folders on the computer.

The photographs taken in this manner were opened in a computer program, where the two contact points between the liquid drop and the surface had to be manually marked. Subsequently, two tangents were manually drawn, and the program calculated the edge angle, which was then saved in an Excel file. Four measurements were taken from each photograph to minimize measurement errors.

SMIC lead-free EcoSolder solder paste was used for soldering due to its safety as a lead-free option.

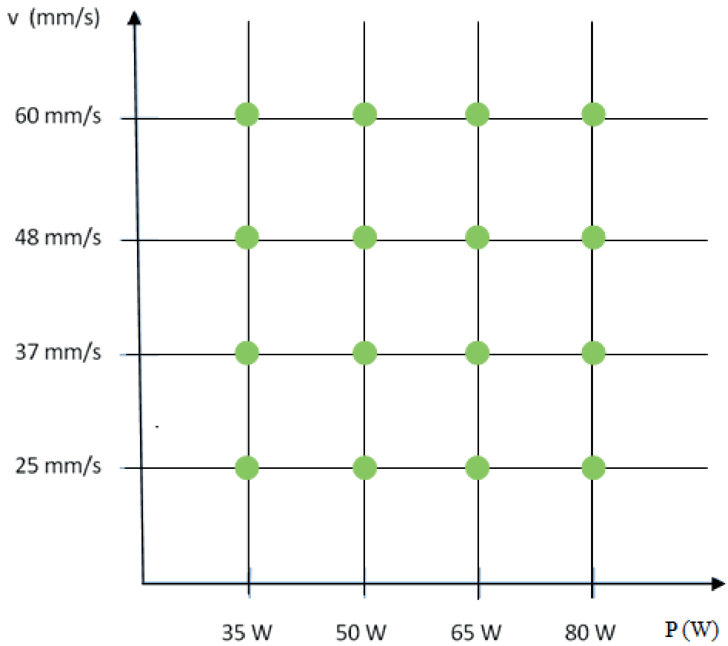

***Figure 2** The parameters of the laser surface treatment*

***Table 1** Chemical composition of M705-GRN360-K1-V solder paste [16]*

%	Sn	Pb	Sb	Bi	Cu	Au	In	Ag	Al	As	Cd	Fe	Ni	Zn
M705	96.5	0.05 max	0.1 max	0.1 max	0.5 max	0.05 max	0.1 max	3 max	0.001 max	0.03 max	0.002 max	0.02 max	0.01 max	0.01 max

A big advantage is that those pastes are available in a wide range of products according to different soldering temperatures. The solder paste utilized carries the type number M705-GRN360-K1-V, with a melting point of around 220 °C according to the manufacturer's data. The chemical composition of the solder paste is shown in Table 1.

3 Result and discussions

Based on the results, it can be seen that compared to samples with untreated surfaces, the wetting values were improved with the CO_2 laser beam (Figure 3). Regarding the trend of the results, it can be said that by increasing the amount of energy input and reducing the feed speed, the value of the wetting edge angle can be reduced. On the DP600 steel plate, wetting improved by 62° for ethylene glycol (Figure 3/b) and 86.5° for distilled water (Figure 3/a), resulting in an improvement of 93.9% and 97.7%, respectively. The alteration of the edge angle values is presumably due to changes in the oxide layer, which was modifiable with the laser beam.

For this treatment, the total interfacial energy was calculated as well, based on the Fawkes relation, as indicated in (Figure 4). The figure shows that the surface energy increases proportionally with increasing power and decreasing feed rate. The surface energy was

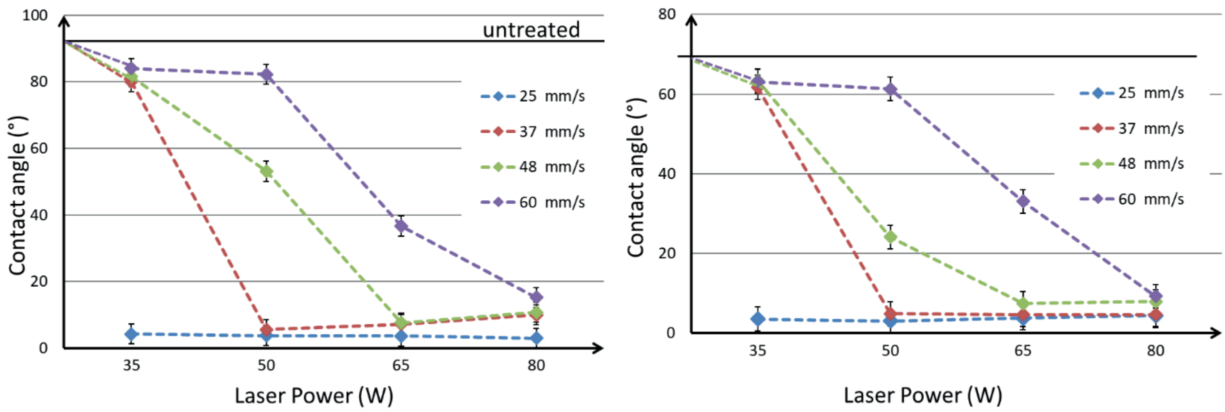

Figure 3 *Effect of the DP600 steel laser surface treatment on the wetting edge angle measured with a) distilled water, b) ethylene glycol liquids*

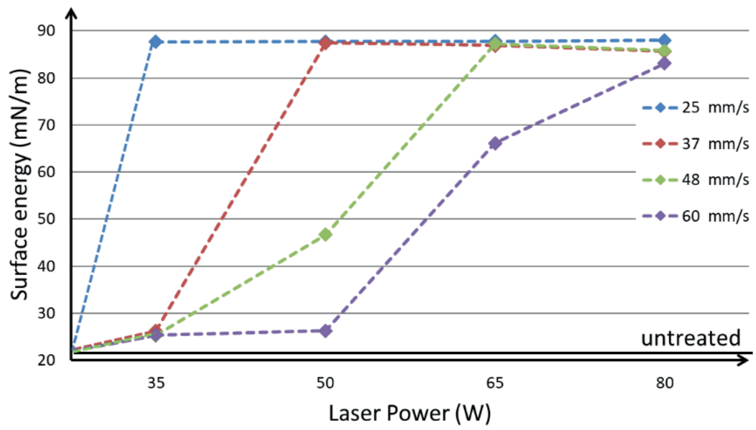

Figure 4 *The change in the interfacial energy as a result of the laser beam surface treatment of DP600 steel*

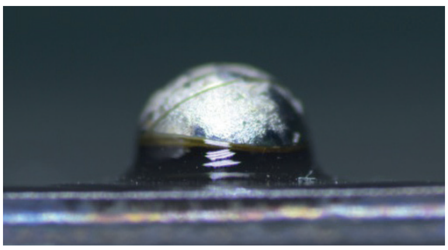

Figure 5 *Contact conditions during the soldering experiment on a laser-treated DP600 steel plate*

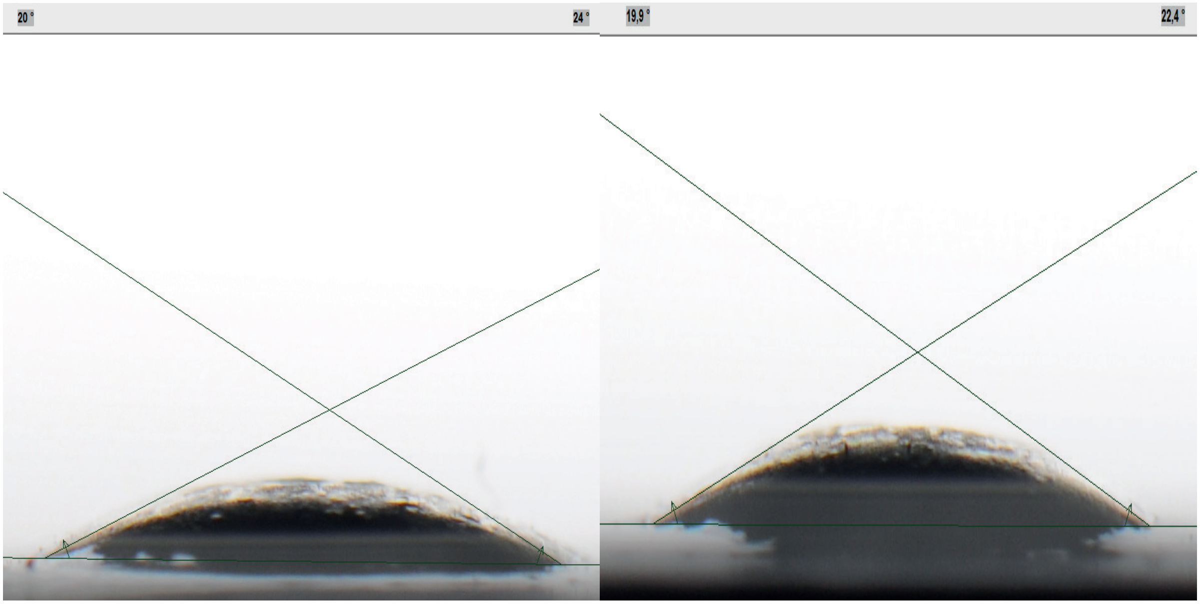

Figure 6 *Images of contact angle measurements of soldering made on an untreated DP600 plate*

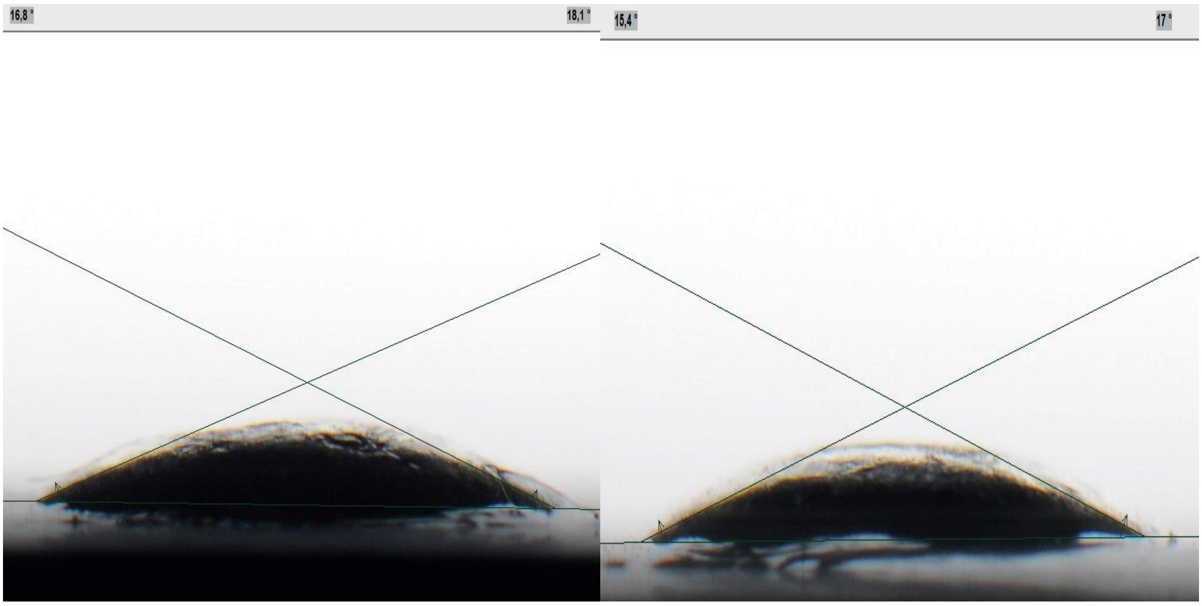

Figure 7 *Images of contact angle measurements of soldering made on laser treated DP600 plate*

almost quadrupled compared to the untreated plate.

A soldering experiment was also performed on the plate treated with the ALFA-LCE 2 laser machine. In this case, the plate was soldered using a power of 50 W and a speed of 37 mm/s. In Figure 5 can be observed that the edge angle of the solder material increased significantly, possibly due to the high temperature, causing the effect of the laser surface treatment to disappear. As a result, the soldering experiment did not yield any results. However, an improvement in bonding is expected with adhesive bonding technologies where the high temperatures are not involved.

Figure 6 shows the soldering measured on the untreated plate, while Figure 7 shows the soldering of the plate treated with 300 W. Each soldering photo was evaluated four times, and the angles were then averaged. The average of the peripheral angle of the soldering on the untreated plate is 20.6°, while the average of the peripheral angle of the soldering measured on the plate treated with 300 W is 16.8°.

Compared to the untreated case, a significant difference can be discovered of the edge angle values of the solder material of the DP600 plate treated with the 300 W laser energy wave. On the one hand, there is an average difference of more than 4°, so the laser beam treatment improves the wetting properties by that much. The standard deviation of the perpendicular angle measurements was improved by approximately

40%, as well, which further strengthens the assumption that the laser treatment does not only result in surface activation, but also in the surface homogenization, which remains even at the soldering temperature.

4 Conclusion

The findings of the study reveal significant enhancements in the wetting values following the CO_2 laser beam surface treatment, in comparison to untreated samples. The trend observed indicates that the increasing energy input and reducing the feed rate contribute to a reduction in the wetting edge angle. On the DP600 steel plate, wetting improved by 62° for ethylene glycol and 86.5° for distilled water, resulting in remarkable improvements of 93.9% and 97.7%, respectively. These changes of the edge angle values are likely attributed to modifications in the oxide layer, achievable through the laser beam treatment. Furthermore, the investigation included calculating the total interfacial energy using the Fowkes relation. The results depicted in Figure 4 illustrate that the surface energy increases proportionally with higher power and decreased feed rate. Notably, the surface energy was nearly quadrupled compared to untreated plates, showcasing the effectiveness of the laser surface treatment. However, in the context of soldering experiments, performed on the plate treated with the ALFA-LCE 2 laser machine, using a power of 50 W and a speed of 37 mm/s, an unexpected increase in the edge angle of the solder material was observed. That increase may be attributed to the high temperature during the soldering process, which could nullify the beneficial effects of the laser surface treatment. Consequently, the soldering experiment did not yield the expected results. In summary, the study underscores the beneficial effects of CO_2 laser beam surface treatment on enhancing the wetting values and surface energy. However, the effects on soldering require further investigation, and adhesive bonding methods may be a promising avenue for improved bonding in the laser-treated materials.

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Conflicts of 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.

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