Technologia i Automatyzacja Montażu

Volume 126, Issue 4/2024, Pages 28-36
https://doi.org/10.7862/tiam.2024.4.4

Original Research

ANALYSIS OF THE POSSIBILITIES OF IMPLEMENTING ALTERNATIVE METHODS OF JOINING SEMIFINISHED PRODUCTS IN THE PRODUCTION PROCESS OF STEEL RIMS

ANALIZA MOŻLIWOŚCI WDROŻENIA ALTERNATYWNYCH METOD ŁĄCZENIA PÓŁWYROBÓW W PROCESIE PRODUKCJI FELG STALOWYCH

Izabela MITURSKA-BARAŃSKA[1,*], Michał BORNUS[2], Rafał SZADURA[2]

[1] Lublin University of Technology, Faculty of Mechanical Engineering, Department of Computerization and Production Robotization, Nadbystrzycka 36, 20-618 Lublin, Poland

[2] MW Lublin Sp. z o.o., Mełgiewska 7/9, 20-209 Lublin, Poland

* Corresponding author: i.miturska@pollub.pl

Abstract

Assembly technology plays a crucial role in the manufacturing process, influencing the efficiency, quality, cost and lead time of production. Assembly technology in the manufacturing process encompasses all techniques and methods used to join components into a finished product. Depending on the industry and specific requirements, assembly technologies can include a variety of techniques, from traditional mechanical joints to advanced bonding, welding or soldering methods. The paper analysed the feasibility of implementing alternative methods of joining blanks in the steel wheel manufacturing process. Testing was carried out to replace the wheel rim flash welding process with laser welding. The effectiveness of laser welding was evaluated by testing prepared butt jointed sheet samples. Tests were carried out on two types of structural steel: S355MC and DD11, which were subjected to flash welding and laser welding. The specimens were subjected to strength and macrographic tests to analyse their structure and mechanical properties. The results showed that laser welding for DD11 steel leads to an increase in tensile strength, while for S355MC steel this strength is reduced. Statistical analysis showed no significant differences between the assembly methods used and the steel types. Macrographic tests confirmed the presence of oxides and other characteristics of the assembly methods used. The results suggest that the choice of the appropriate joining method can have a significant impact on the quality and durability of the final product, which is crucial in the context of steel wheel production.

Keywords: assembly, flash welding, laser welding, strength

Streszczenie

Technologia montażu odgrywa kluczową rolę w procesie produkcyjnym, wpływając na efektywność, jakość, koszty oraz czas realizacji produkcji. Technologia montażu w procesie produkcyjnym obejmuje wszystkie techniki i metody używane do łączenia komponentów w gotowy produkt. W zależności od branży i specyficznych wymagań, technologie montażu mogą obejmować różnorodne techniki, od tradycyjnych połączeń mechanicznych po zaawansowane metody klejenia, spawania czy lutowania. W pracy przeanalizowano możliwości wdrożenia alternatywnych metod łączenia półwyrobów w procesie produkcji felg stalowych. Przeprowadzono próby zastąpienia procesu zgrzewania iskrowego obręczy koła spawaniem laserowym. Skuteczność spawania laserowego oceniano badając przygotowane próbki blach łączonych doczołowo. Badania przeprowadzono na dwóch rodzajach stali konstrukcyjnej: S355MC i DD11, które zostały poddane zgrzewaniu iskrowemu oraz spawaniu laserowemu. Próbki poddano testom wytrzymałościowym oraz makrograficznym w celu oceny ich struktury i właściwości mechanicznych. Wyniki badań wykazały, że spawanie laserowe w przypadku stali DD11 prowadzi do wzrostu wytrzymałości na rozciąganie, podczas gdy w przypadku stali S355MC wytrzymałość ta ulega obniżeniu. Analiza statystyczna nie wykazała istotnych różnic między zastosowanymi metodami montażu a rodzajami stali. Badania makrograficzne potwierdziły obecność tlenków oraz inne cechy charakterystyczne dla zastosowanych metod montażu.

Wyniki sugerują, że wybór odpowiedniej metody łączenia może mieć istotny wpływ na jakość i trwałość końcowego produktu, co jest kluczowe w kontekście produkcji felg stalowych.

Słowa kluczowe: montaż, zgrzewanie iskrowe, spawanie laserowe, wytrzymałość

1. Introduction

Assembly technology plays a fundamental role in many industries, including the automotive industry, affecting almost every aspect of vehicle production (Uchihara, 2011). First and foremost, effective assembly technology is crucial to ensure high quality and precision in production, which translates into safety, reliability and durability of finished vehicles. Advanced assembly methods such as automation, robotics and techniques such as welding, resistance welding and bonding enable the creation of components with high strength and accuracy (K Srivastava & Sharma, 2017).

The implementation of high-tech assembly technologies significantly improves manufacturing efficiency, allowing for rapid and automated assembly of parts, which reduces production time and manufacturing costs (Cohen, Naseraldin, Chaudhuri, & Pilati, 2019). As a result, automotive companies can produce vehicles on a larger scale, meeting growing market demand while maintaining competitive prices.

One of the steps in the vehicle manufacturing process is the steel wheel production process, where assembly technology plays a crucial role, influencing every stage of the product creation. First and foremost, proper assembly methods ensure that the various parts of the rim, such as the rim and disc, are precisely and permanently joined together, which is essential to ensure the safety and reliability of the finished product. Advanced techniques, such as laser welding or flash welding, make it possible to create high-strength joints while minimising the weight of the rim, which is important for vehicle performance (Fysikopoulos, Pastras, Stavridis, Stavropoulos, & Chryssolouris, 2016).

The implementation of high-tech assembly technologies also affects the efficiency of the manufacturing process. The automation and robotisation of assembly processes allows an increase in production speed, while reducing the risk of defects and lowering manufacturing costs (Perka, John, Kuruveri, & Menezes, 2022; Xu, Shi, Cui, & Liang, 2023). As a result, higher production efficiencies can be achieved, which has a direct impact on competitiveness in the automotive industry.

Assembly technology also influences production flexibility, enabling rapid adaptation to changing industry requirements, such as the introduction of new rim models. In addition, choosing the right assembly methods is environmentally relevant, as it can lead to a reduction in energy and material consumption, which promotes sustainable production. As a result, assembly technology is a crucial element in the production process of steel rims, having a direct impact on the quality, efficiency and innovation of the final product (I Miturska & Rudawska, 2021; I Miturska, Rudawska, Pawlak, Stančeková, & Chyra, 2017).

Another important aspect is the sustainability impact of assembly technology. Choosing energy-efficient and less resource-intensive assembly methods contributes to reducing the carbon footprint of the production process, which is increasingly important in the context of global environmental requirements (K Srivastava & Sharma, 2017; Szala & Lukasik, 2018).

The aim of this study was to carry out a specific analysis of the possibility of implementing alternative methods of joining blanks in the production process of steel wheels. This analysis was made possible by assessing the efficiency and strength of the joints made using laser welding, compared to the traditional method so far used in the process under study, which is flash welding. Two types of structural steel were used in this study: S355MC and DD11. From these materials, specimens were prepared by butt welding and laser welding. The joints were tested for strength and structural properties.

1.1. Flash butt welding

Flash welding is an assembly method that plays a fundamental role in the process of joining metals, especially in the automotive, construction and appliance industries. The process involves welding the ends of two metal parts that are pressed together and heated simultaneously, leading to melting and re-solidification (Kimchi & Phillips, 2023). During flash butt welding, it is important that the quality and characteristics of the weld are adequate, as these determine the strength and durability of the joint. The weld is often homogeneous with the base materials to ensure good electrical conductivity and favourable mechanical properties. Flash butt welding is used in the manufacture of cables, pipes, as well as in the construction of automobiles and various appliances (Al-Mukhtar, 2016).

There are several steps in the electrical flash welding process, which is the most commonly used method. Initially, the workpieces are pressed against each other and then an electric current is switched on, leading to the release of heat at the contact surface. As the temperature rises, the metal plasticises and the pressing force causes deformation. When the current is switched off, the weld remains under pressure, allowing the metal to solidify (Biradar & Dabade, 2020).

The main methods used in the electrical spark welding process are alternating current (AC) and direct current (DC) welding (Balaraju, Sankara Narayanan, & Seshadri, 2003; Hajializadeh & Mashhadi, 2015). These methods differ in both equipment design and process characteristics.

AC resistance welding involves the use of alternating current, which means that the supply voltage changes direction at regular intervals. With AC resistance welding machines, the resistance welding process relies on transformers that convert the mains voltage to the appropriate values for the resistance welding process.

On the other hand, DC flash welding uses direct current, which allows for a more stable and controlled flash welding process. DC-powered devices can be designed as three-phase spark welding machines or average frequency inverters (MF/DC). DC flash welders are characterised by a higher power rating and better control of the spark welding parameters, resulting in higher joint quality. With DC flash welding, the current is rectified, resulting in more homogeneous and stronger welds.

In the process of manufacturing steel wheels, both of the methods described are applicable.

1.2. Laser welding

Laser sheet metal welding is a modern material joining technique that uses a concentrated laser beam as a heat source to fuse the edges of the parts to be joined. This method is characterised by high precision, speed and minimal impact on surrounding materials, making it an attractive alternative to traditional flash welding techniques (Mei et al., 2015; Mei, Yi, Yan, Liu, & Chen, 2012).

n laser welding, there are two main modes: conduction welding and deep-fusion welding. In conduction welding, the laser beam heats the surface of the material to its melting point, leading to the formation of a weld pool (Hong & Shin, 2017). This technique is particularly effective for thin-film materials where the aesthetics of the weld are important. Deep-fusion welding, on the other hand, involves heating the material to the point of evaporation, resulting in deeper and narrower welds, ideal for joining thick plates (Manoharan, Bashir, & Zaifuddin, 2020; Rossini, Spena, Cortese, Matteis, & Firrao, 2015).

One of the main advantages of laser welding is the small heat affected zone, which minimises the risk of material distortion and subsequent processing requirements. The high precision and repeatability of the process make laser welding widely used in a variety of industries.

These techniques also make it possible to join materials with different properties, such as steel and aluminium, which is important in the context of modern construction where material diversity is common. Laser welding can be used in both continuous and pulsed modes, allowing the process to be adapted to specific production requirements (Fernandes, Oliveira, & Pereira, 2017).

The development of laser technology and the automation of welding processes in recent years have contributed to increased efficiency and lower production costs, making laser welding increasingly popular in industry. As technology advances, this method can be expected to develop further, opening up new possibilities for joining materials (Manoharan et al., 2020).

2. Experimental studies

2.1. Materials

The materials used in the study were sheets of two types of structural steel: S355MC and DD11, which are used in the manufacturing process of steel wheels.

S355MC steel is a type of structural steel that is characterised by increased strength, Rm = 430-550 MPa, and good ductility with a minimum yield strength of 355 MPa (*https://www.steelnumber.com/en/steel_composition_eu.php?name_id=206*, 2024). S355MC steel is particularly valued in civil engineering, where it is used for structures subjected to dynamic and fluctuating loads. The chemical composition of S355MC steel is shown in Table 1.

Table 1. Chemical composition % of steel S355MC (*https://www.steelnumber.com/en/steel_composition_eu.php?name_id=206*, 2024)

Component	Amount
C	max 0.120
Si	max 0.500
Mn	max 1.500
P	max 0.025
S	max 0.020
V	max 0.200
Nb	max 0.090
Ti	max 0.150
Al	max 0.015
The sum of Nb, V and Ti shall be max 0.22 %	

It is worth pointing out that S355MC steel is used in a variety of industries, including the automotive industry, where it is used to manufacture components subjected to varying loads. Its properties make it suitable for applications requiring high strength and durability.

The second material used in the study was DD11 steel. DD11 steel has excellent ductility, with a minimum yield strength of 360 MPa and a strength of Rm = 440 MPa (*https://www.steelnumber.com/en/steel_composition_eu.php?name_id=218*, 2024). The chemical composition of DD11 steel is shown in Table 2.

Table 2. Chemical composition % of steel DD11 (*https://www.steelnumber.com/en/steel_composition_eu.php?name_id=218*, 2024)

Component	Amount
C	max 0.120
Mn	max 0.600
P	max 0.045
S	max 0.045

The properties of DD11 steel make it suitable for a variety of applications, such as load-bearing structures and transport components. Although it is not galvanised, its surface is adequately protected against corrosion, which increases its durability in industrial applications. The steel is also abrasion resistant, which is an important advantage in applications where the material is exposed to intensive use and mechanical stresses.

2.2. Specimens

Specimens prepared from the materials described were used for testing. Strips of sheet metal with the dimensions shown in Figures 1 and 2 were joined together, and the specimens to be tested were then cut out, with a width of 25 mm.

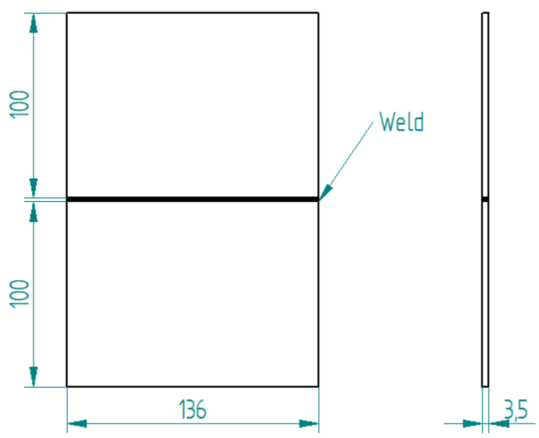


Fig. 1. Dimensions and geometry of S355MC steel specimens

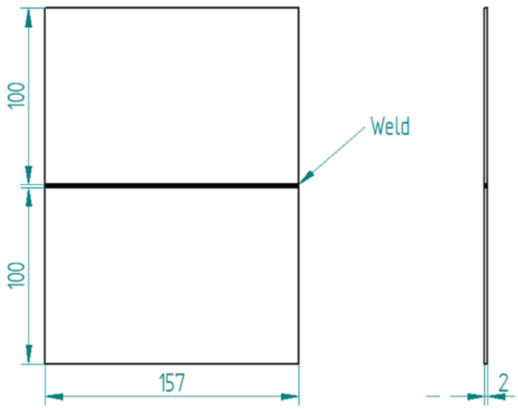


Fig. 2. Dimensions and geometry of DD11 steel specimens

For comparison purposes, the native material was also tested, For this purpose, specimens of 100 mm x 25 mm were cut from sheets of each material. The thickness of the specimens depended on the type of material, as shown in Figures 1 and 2. 10 specimens were prepared for each type of joint and each material.

2.3. Specimens preparation

The specimens to be tested were prepared using two assembly methods: electrical flash welding and laser welding.

2.3.1. Electric flash welding

The welding process was carried out in accordance with the guidelines that apply to the production process for steel wheels. The material was not specially prepared before the process. Some of the data relating to the welding process is confidential and therefore not all data can be made public. The butt-welding process was carried out using a DC welding machine with a 630 kVA transformer. The electrodes used in the process are made of CNCS copper and are 280 mm long. After the butt-welding process, the weld was trimmed and rolled in the specimens to be tested for strength, in order to remove the hump created during the weld forming process, according to the guidelines of the actual process.

2.3.2. Laser welding

The alternative assembly method proposed for butt flash welding the sheets was laser welding. In order to replicate the production conditions as possible, the materials were not subjected to any special treatment before the welding process. Laser welding was realised using a Fanuci 4.0 Pro GenX handheld welding laser with a fibre source power of 3kW. The components of the laser welding station are shown in Figure 3.

Fig. 3. Construction of a laser welding station

The working tool in the laser welding station, and at the same time the most essential one, is the laser head. Its construction is shown in Figure 4.

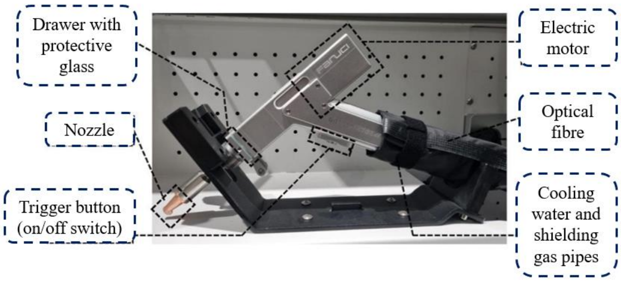


Fig. 4. Construction of a GenX laser head

Taking into account the properties of the materials to be joined and their dimensions, in particular the thickness, appropriate parameters were selected for the laser welding process. The welding parameters used are summarised in Table 3.

Table 3. Process parameters for laser welding

Parameter	S355MC	DD11
Welding wire	Ø1.6 mm Esab OK Autrod 12.64	Ø1.6 mm Esab OK Autrod 12.64
Shielding gas	100% argon Compressed argon 2.2	100% argon Compressed argon 2.2
Scanning width	3.0 mm	3.0 mm
Power	1 450 W	1 500 W
Wire feed speed	400 mm/min	800 mm/min
Scanning speed	300 mm/s	300 mm/s
Frequency	5 000 Hz	5 000 Hz

Using the above parameters, the sheets were butt jointed.

3. Research results and discussion

The specimens were subjected to strength tests and macrographic tests to assess their structure. The results obtained are shown below.

3.1. Strength test results

Strength tests were carried out using a Zwick Roell Z150 strength testing machine in accordance with PN-EN 10002-1:2004 test standard (*PN-EN 10002--1:2004 - Metallic materials - Tensile testing - Part 1: Method of test at ambient temperature*, 2004). The results are shown in Figures 5 and 6.

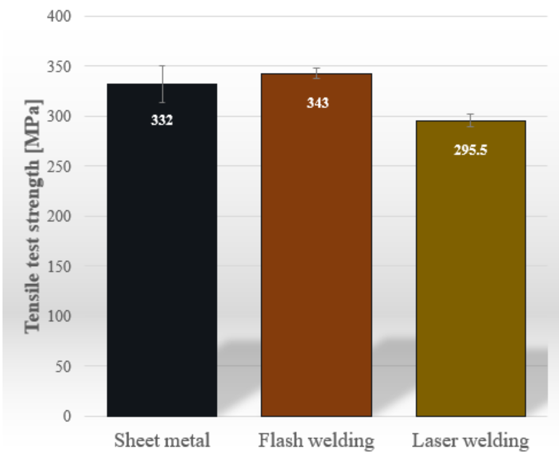


Fig. 5. Test results of tensile test strength of S355MC

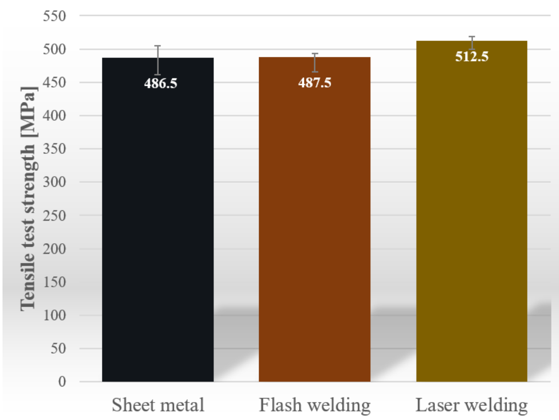


Fig. 6. Test results of tensile test strength of DD11

The obtained test results show that for the specimens made of S355MC sheet the average tensile strength for the raw sheet is 332 MPa, which is the basis for comparison with the samples after welding. The average tensile strength after flash welding increases slightly to 343 MPa. This slight increase suggests that flash welding can lead to favourable changes in the microstructure of S355MC steel, which can strengthen the material. The low variability of the results indicates that flash welding is a reproducible process that does not result in large differences in tensile strength between samples. With laser welding, the tensile strength decreases to 295.5 MPa, which is the lowest value compared to the other samples. The decrease in strength after laser welding may be due to defects, such as microcracks or changes in the crystal structure, which can weaken the material. This can also be evidenced by the fact that only in these joints did the failure occur at the weld site. The standard deviation of all analysed groups of samples represents between 1.6 % and 5.5 % of the average strength, suggesting that the strength test results were stable and did not show much variability. This means that the material had a uniform structure and consistent mechanical properties.

For the specimens made from DD11 sheet, the average tensile strength value for the reference specimens is 486.5 MPa. For the flash-welded specimens, the strength increases minimally to 487.5 MPa, suggesting that this method does not have a significant effect on reducing the strength of the material,. For the laser-welded specimens, the average tensile strength increases to 512.5 MPa, indicating an improvement in the material's mechanical properties compared to the baseline.

A statistical analysis of the results obtained was also carried out to verify whether the differences occurring between the various assembly methods and materials were significant. A significance level of $\alpha=0.05$ was adopted and a one-way ANOVA analysis was performed. However, the results obtained did not show any significant differences between the results analysed.

3.2. Macrographic results

The results of the macrographic tests are shown in the figures in Tables 7-10. The samples were polished to check for the presence of oxides on the surface and etched using the Bechet-Beaujet method to better examine the internal geometry of the weld.

Table 7. Macrographic test results - flash welding joints of S355MC steel

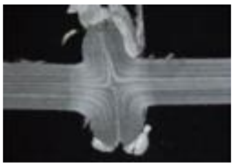
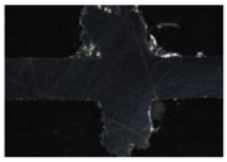
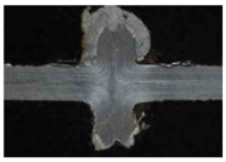
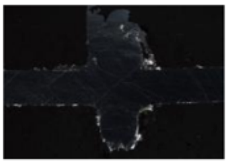
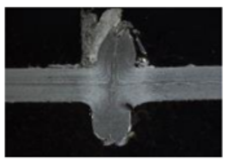
Section	**Polishing only**	**Etching Bechet-Beaujet**
Start		
Centre		
End		

Table 8. Macrographic test results - laser welding joints of S355MC steel

Section	**Polishing only**	**Etching Bechet-Beaujet**
Start		
Centre		
End		

Table 9. Macrographic test results - flash welding joints of DD11 steel

Section	**Polishing only**	**Etching Bechet-Beaujet**
Start		
Centre		
End		

The aim of the macrographic tests was, among other things, to check for the presence of oxides on the bonded surface. The presence of oxides can affect the quality of the weld and lead to defects that can weaken the strength of the joint. By analysing the cross-sections of the joints made of S355MC steel, it can be seen that in the case of flash-welded joints, oxides were not present on the surface. In the case of laser-welded joints, oxides were present on the surface of the weld. By analysing the cross-section of the etched specimens, it can be observed that, in the case of the flash-welded specimens, characteristic structures are visible, indicating material flow at the joint. The laser-welded cross-sections presented structural defects. Inclusions, pores and impurities in the weld are visible. Such defects can affect mechanical properties, including fracture toughness and compressive and tensile strength.

Table 10. Macrographic test results - laser welding joints of DD11 steel

Section	**Polishing only**	**Etching Bechet-Beaujet**
Start		
Centre		
End		

By analysing the cross-sectional images of the joints made from DD11 steel, it can be seen that, as in the case of the specimens made from S355MC steel, oxides are present on the surface of the laser-welded joints. The flash-welded joints are characterised by a homogeneous structure. The microstructure in the weld cross-section of the laser-welded joints shows some inhomogeneities, such as the presence of inclusions, but in a smaller amount than in the laser-welded joints of S355MC sheet.

Laser welded joints have a large number of imperfections (visible pores), which can be caused by several factors.

Firstly, laser welding is a very precise technique, but in the case of materials with a complex microstructure, such as S355MC structural steel, defects such as micro-cracks or changes in the crystal structure can occur. Such defects can weaken the material, causing cracks or the formation of pores.

Secondly, Laser welding requires the precise selection of parameters such as laser power, welding speed or type of shielding gas. Improper settings can lead to excessive material evaporation or uneven melting, resulting in pores and other defects in the welds. In the study presented here, the parameters used in the research were chosen experimentally, and perhaps an improvement in the parameters would have alleviated the problem in the weld structure.

Thirdly, the formation of oxides on the weld surface can occur during laser welding, as shown in the macrographic results. Oxides and other inclusions can lead to imperfections in the weld structure, weakening its strength and causing pores to form.

Fourthly, although there is a small heat affected zone in laser welding, which minimises material distortion, it can at the same time promote the formation of defects, particularly in areas of thicker material or where the filler material does not distribute uniformly.

In summary, it can be concluded that imperfections in the form of pores in laser welds are due to a combination of process-related factors such as micro-cracks, structural defects, the presence of oxides and difficulties in optimally setting the welding parameters.

4. Conclusion

Assembly technology is a fundamental aspect of steel wheel production, and plays an important role in ensuring the high quality and durability of the finished product. Tests carried out on samples of S355MC and DD11 steel, using two assembly methods - electrical flash welding and laser welding - allowed the efficiency and strength of the joints made using these techniques to be assessed.

The results of the strength tests showed that electrical flash welding provided more stable and repeatable joints, especially for S355MC steel, while laser welding, despite its higher precision, could lead to structural defects that weaken the material. In the case of DD11 steel, laser welding improved the mechanical properties compared to the baseline.

Macrographic tests revealed that oxides were present on the surface of laser-welded joints, which may affect the quality and strength of the joints, while flash-welded joints were characterised by a more homogeneous structure.

Based on the research carried out, the following conclusions can be formulated:

- Flash electric welding is a more efficient assembly method in terms of stability and repeatability of results, especially for S355MC steel, where it minimizes the risk of structural defects. This may be related to this method's lower propensity to cause structural defects in mild steels. The decrease in strength after laser welding may be due to increased brittleness or the formation of defects in the microstructure of the steel during welding.

- Laser welding can lead to microcracks and other defects that can reduce the strength of the joints, which was particularly evident in S355MC steel samples. However, in the case of DD11 steel, laser welding resulted in improved mechanical properties, suggesting that the method may be beneficial depending on the material used. This may be due to less heat input and a more homogeneous microcrystalline structure obtained during laser welding
- The comparison of the results shows that the mechanical properties and the choice of the appropriate joining technique can differ significantly depending on the type of steel, which should be taken into account in the design and production process. However, as the statistical analysis showed, in the analyzed cases the differences that occur are statistically insignificant.
- The cross-sectional analysis shows how various factors can affect the microstructure of the material at the junction. In the heat-affected zone, changes in the crystal structure can be expected, which can lead to the formation of phases such as martensite, bainite or pearlite, depending on the cooling process.
- The presence of oxides on the surface of laser-welded joints is a significant problem that can affect the durability and strength of the joints, which requires further research into optimizing laser welding parameters.
- Analysis of the etched samples shows that both flash-welds and laser-welds can contain structural inhomogeneities, such as changes in remelting geometry and the presence of micropores or inclusions. In the case of the DD11 material, which is a steel with good ductility but low strength, these defects can have a significant impact on the strength of the joints.
- The use of modern assembly technologies such as laser welding, despite some advantages, requires detailed analysis in the context of specific applications and material properties to guarantee optimal quality and durability of products.

In conclusion, the choice of an appropriate assembly method in the manufacturing process should always be made taking into account the specific properties of the materials used, application requirements, especially regarding the strength of the joints, cost effectiveness, as well as the impact on the environment and the sustainability of production. Therefore, in order to continue the discussed issue, further research will focus on optimizing laser welding parameters, evaluating the durability of joints under operating conditions, and cost calculation taking into account the adaptation of the laser welding process in the actual production process of steel rims.

References

Al-Mukhtar, A.M. (2016). Review of Resistance Spot Welding Sheets: Processes and Failure Mode. *Advanced Engineering Forum*, *17*, 31–57. doi: 10.4028/www.scientific.net/AEF.17.31.

Balaraju, J.N., Sankara Narayanan, T.S.N., Seshadri, S.K. (2003). Electroless Ni–P composite coatings. *Journal of Applied Electrochemistry*, *33*(9), 807–816. doi: 10.1023/A:1025572410205.

Biradar, A.K., Dabade, B.M. (2020). Optimization of resistance spot welding process parameters in dissimilar joint of MS and ASS 304 sheets. *Materials Today: Proceedings*, *26*, 1284–1288. doi: 10.1016/j.matpr.2020.02.256.

Cohen, Y., Naseraldin, H., Chaudhuri, A., Pilati, F. (2019). Assembly systems in Industry 4.0 era: A road map to understand Assembly 4.0. *The International Journal of Advanced Manufacturing Technology*, *105*(9), 4037–4054. doi: 10.1007/s00170-019-04203-1.

Fernandes, F.A.O., Oliveira, D.F., Pereira, A.B. (2017). Optimal parameters for laser welding of advanced high-strength steels used in the automotive industry. *Procedia Manufacturing*, *13*, 219–226. doi: 10.1016/j.promfg.2017.09.052.

Fysikopoulos, A., Pastras, G., Stavridis, J., Stavropoulos, P., Chryssolouris, G. (2016). On the Performance Evaluation of Remote Laser Welding Process: An Automotive Case Study. *Procedia CIRP*, *41*, 969–974. doi: 10.1016/j.procir.2016.01.005.

Hajializadeh, F., Mashhadi, M.M. (2015). Investigation and numerical analysis of impulsive hydroforming of aluminum 6061-T6 tube. *Journal of Manufacturing Processes*, *20*, 257–273. doi: 10.1016/j.jmapro.2015.06.027.

Hong, K.-M., Shin, Y.C. (2017). Prospects of laser welding technology in the automotive industry: A review. *Journal of Materials Processing Technology*, *245*, 46–69. doi: 10.1016/j.jmatprotec.2017.02.008.

Https://www.steelnumber.com/en/steel_composition_eu.php?name_id=206. (2024).

Https://www.steelnumber.com/en/steel_composition_eu.php?name_id=218. (2024).

K Srivastava, A., Sharma, A. (2017). Advances in Joining and Welding Technologies for Automotive and Electronic Applications. *American Journal of Materials Engineering and Technology*, *5*(1), 7–13. doi: 10.12691/materials-5-1-2.

Kimchi, M., Phillips, D.H. (2023). *Resistance spot welding: Fundamentals and applications for the automotive industry* (Second edition). Cham: Springer.

Manoharan, K.A., Bashir, M.N., Zaifuddin, A.Q. (2020). An Overview of Laser Welding of High Strength Steels for Automotive Application. *International Journal of Technology and Engineering Studies*, *6*(1), 23–40. doi: 10.20469/ijtes.6.10004-1.

Mei, L., Yan, D., Chen, G., Xie, D., Zhang, M., Ge, X. (2015). Comparative study on CO2 laser overlap welding and resistance spot welding for automotive body in white. *Materials & Design*, *78*, 107–117. doi: 10.1016/j.matdes.2015.04.031.

Mei, L., Yi, J., Yan, D., Liu, J., Chen, G. (2012). Comparative study on CO2 laser overlap welding and resistance spot welding for galvanized steel. *Materials & Design*, *40*, 433–442. doi: 10.1016/j.matdes.2012.04.014.

Miturska, I, Rudawska, A. (2021). Structural factors influence on strength properties of S235JR steel welded joints. *Journal of Physics: Conference Series*, *1736*(1), 012004. doi: 10.1088/1742-6596/1736/1/012004.

Miturska, I., Rudawska, A., Pawlak, P., Stančeková, D., Chyra, M. (2017). Comparative Analysis of Welded and Adhesive Joints Strength Made of Acid-Resistant Stainless Steel Sheets. *Advances in Science and Technology Research Journal*, *11*(4), 97–102. doi: 10.12913/22998624/78165.

Perka, A.K., John, M., Kuruveri, U.B., Menezes, P.L. (2022). Advanced High-Strength Steels for Automotive Applications: Arc and Laser Welding Process, Properties, and Challenges. *Metals*, *12*(6), 1051. doi: 10.3390/met12061051.

PN-EN 10002-1:2004—Metallic materials—Tensile testing—Part 1: Method of test at ambient temperature. (2004).

Rossini, M., Spena, P.R., Cortese, L., Matteis, P., Firrao, D. (2015). Investigation on dissimilar laser welding of advanced high strength steel sheets for the automotive industry. *Materials Science and Engineering: A*, *628*, 288––296. doi: 10.1016/j.msea.2015.01.037.

Szala, M., Łukasik, D. (2018). Pitting Corrosion of the Resistance Welding Joints of Stainless Steel Ventilation Grille Operated in Swimming Pool Environment. *International Journal of Corrosion*, *2018*, 1–7. doi: 10.1155/2018/9408670.

Uchihara, M. (2011). Joining technologies for automotive steel sheets. *Welding International*, *25*(4), 249–259. doi: 10.1080/09507111003655341.

Xu, T., Shi, Y., Cui, Y., Liang, Z. (2023). Effects of Magnetic Fields in Arc Welding, Laser Welding, and Resistance Spot Welding: A Review. *Advanced Engineering Materials*, *25*(5), 2200682. doi: 10.1002/adem.202200682.