ACTA METALLURGICA SLOVACA
2025, VOL. 31, NO. 4, 259-263

RESEARCH PAPER

Numerical simulation–based optimization of clinching processes for high-strength steel sheets

Ľuboš Kaščák[1], *Ján Varga*[1], *Tomáš Jezný*[1], *Tibor Kvačkaj*[2]

[1]Technical University of Košice, Faculty of Mechanical Engineering, 042 00 Košice, Slovakia
[2]Bodva Industry and Innovation Cluster, Budulov 174, 04501 Moldava nad Bodvou, Slovakia

*Corresponding author: lubos.kascak@tuke.sk, Tel.: 055/6023508, Department of Technology, Materials and Computer Supported Production, Faculty of Mechanical Engineering, Technical University of Košice, Mäsiarska 74, 040 01 Košice, Slovakia

Received: 21.11.2025
Accepted: 28.11.2025

ABSTRACT

The choice of materials for car bodies varies significantly, driven by the dual objectives of minimizing body weight to improve fuel efficiency and enhancing passive safety for occupants. To integrate these diverse materials, a variety of joining techniques are used, including resistance spot welding, mechanical fastening, and adhesive bonding. The selection of materials for car body production is a critical determinant of vehicle performance, safety, manufacturing efficiency, and environmental impact. The car body-in-white (BIW), which serves as the vehicle's structural framework, must meet a diverse set of requirements, including a high strength-to-weight ratio, energy-absorption capacity during crashes, formability, corrosion resistance, and cost-effectiveness. This necessitates the use of a combination of materials, predominantly various grades of steel, along with aluminum alloys, polymers, and composites. Numerical simulations in the process of optimizing clinched joints represent an extremely effective tool that allows us to shorten the time of technology development and reduce the number of time-consuming and financially demanding experimental tests. However, the simulation outputs must be systematically verified and validated against experimental results. Only the combination of a suitable assembly and a reliably functioning numerical model with thorough experimental verification can lead to a technological solution that is operationally safe, secure and economically optimized at the same time. At the same time, the set of knowledge created in this way enables the systematic optimization of process parameters and increases the transferability of the obtained results to industrial practice.

Keywords: clinching; numerical simulation; tensile test; high-strength steel

INTRODUCTION

Over the past two decades, significant research has advanced automotive steels. The primary aim of these investigations, conducted by both academic researchers and steel manufacturers, has been to develop stronger yet lighter steel grades that reduce vehicle weight and improve fuel efficiency, without compromising crash safety performance [1,2]. Automotive manufacturers are continually required to balance fuel economy with stringent safety standards when designing and selecting specific steel grades. Two critical drivers behind the evolution of automotive steels are the reduction of carbon emissions and the enhancement of occupant safety [3,4].

With increasing demands for safety and performance in the automotive sector, a shift has occurred from conventional deep-drawing steels to high-strength steels (HSS) [5]. This transition has been facilitated by the emergence of advanced high-strength steels (AHSS), which exhibit tailored microstructures, superior mechanical properties, and innovative processing techniques. Implementing AHSS enables manufacturers to improve vehicle safety and efficiency while reducing production costs. Furthermore, several research institutions have introduced novel steel concepts enabling optimization of mechanical properties. Studies have shown that replacing conventional steels in a four-door passenger vehicle with AHSS can reduce weight by 14% to 25%, offering both economic and environmental advantages [6,7].

Among the various joining methods employed in automotive manufacturing, resistance spot welding (RSW) remains the most widely used for assembling steel components. RSW is a fusion welding technique that does not require additional filler materials [8]. It operates through the application of opposing electrodes that generate localized heat and pressure to form a weld. This process efficiently joins multiple layers of material, though it can lead to undesirable thermal effects and geometric distortions [9-11]. Despite its dominance in the industry, RSW is primarily suited to similar materials and is limited for joining dissimilar or advanced materials [12,13].

While resistance spot welding (RSW) continues to dominate BIW production, it exhibits well-known challenges for highly alloyed steels, aluminium sheet, and mixed-material stack-ups, particularly with respect to process window, electrode wear, and fatigue performance. Consequently, there has been intense development and industrial adoption of alternative joining methods that can either complement or replace local RSW in car body structures [14].

Among these alternatives, mechanical fastening processes such as clinch-riveting, self-piercing riveting (SPR) and mechanical clinching have become key technologies for lightweight and multi-material BIW concepts. Mechanical joining techniques, in particular, offer the advantage of avoiding heat-related material degradation. Techniques such as clinching, clinch-riveting, and self-piercing riveting (SPR) are now widely used in both automotive and aerospace applications [15-17].

Clinching, a novel mechanical fastening process, enables the formation of high-strength joints without the need for additional components. It relies on plastic deformation and a specially designed tool to form a permanent mechanical interlock between sheet materials [18–20]. The mechanical performance of clinched joints is highly dependent on both joint geometry and processing parameters [21].

As clinching is a combination of material drawing and forming, numerical simulations have proven to be highly effective for process optimization [22]. Finite Element Method (FEM) analysis has emerged as a powerful tool for understanding and optimizing the clinching process of high-strength steel sheets. FEM enables detailed simulation of material flow, stress distribution, and deformation behavior during clinching, allowing researchers and engineers to predict joint quality, identify potential failure modes, and refine tool designs before costly experimental trials [23]. These simulations reduce the need for extensive experimental testing and allow for the prediction of joint behavior under varying conditions. Consequently, simulation-based design approaches are increasingly being adopted to improve cost-efficiency and reduce development time in clinching processes. FEM analysis is integral to advancing the clinching technology for high-strength steel sheets, enabling the design of robust joints and supporting the broader adoption of lightweight, high-performance materials in modern engineering applications [24-28].

The paper deals with optimization of clinching process made on high-strength steel sheets. Numerical simulation was utilized to optimize the clinching process. The numerical simulation results were verified against those from real clinched joints.

MATERIAL AND METHODS

Materials for experiments

DOI: https://doi.org/10.36547/ams.31.4.2260

Double-sided hot-dip galvanized dual-phase steel sheets HCT600X+Z and micro-alloyed steel sheets HX420LAD+Z, both with a thickness of 1.5 mm, were used for the numerical simulation as well as for the experiments. The basic mechanical properties and the chemical composition of these materials are shown in **Tables 1 and 2**. Dual-phase (DP) steels are a highly versatile material for the automotive industry, offering enhanced formability, excellent crash energy absorption, and strong fatigue resistance. Micro-alloyed grade steels are characterized by a fine structure and improved cold formability. The sheets are used for dynamically stressed parts of vehicles.

Table 1 Basic mechanical properties of joined materials

Material	**Rp$_{0.2}$ [MPa]**	**R$_m$ [MPa]**	**A$_{80}$ [%]**
HCT600X+Z	380	600	20
HX420LAD+Z	470	530	17

Table 2 Chemical composition (in [%] of wt) of joined materials

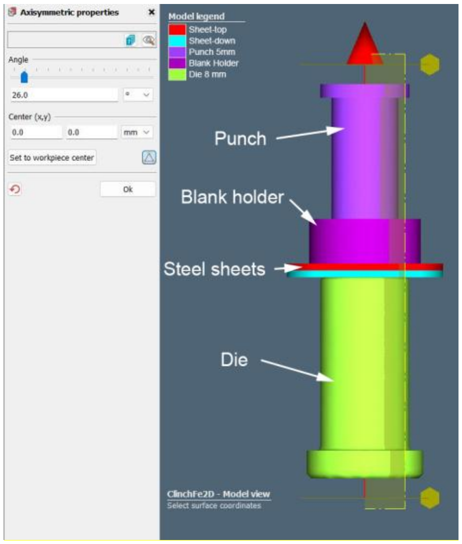
Material	**C**	**Si**	**Mn**	**P**	**Nb**	**Al**	**Ti**
HCT600X+Z	0.09	0.26	1.89	0.014	0.001	0.026	0.003
HX420LAD+Z	0.08	0.20	1.20	0.016	0.006	0.035	0.015

Numerical simulation of clinching process

Simufact Forming software with the Mechanical Joining module was used for numerical simulation of clinching processes. It is a specialized simulation software from Hexagon focused on metal forming processes and mechanical joining. The simulation of the clinching process was solved as a 2D axisymmetric task. **Fig. 1** shows the schematic setup of the 2D model.

Boundary conditions set in clinching simulations:

- Tool: punch ø5 mm, die ø8 mm, blank holder
- Mesh type: Advancing Front Quad
- Mesh element size – 0.125 mm
- Friction: Coulomb friction
- Friction coefficient:
    - between top and bottom sheet = 0.12
    - between tool and sheet = 0.2
- Blank holder force: F=0.5 kN
- Punch stroke: 3.4 mm; 3.6 mm; 3.8 mm; 4.0 mm
- Material damage model: Cockroft-Latham model



Angle 26.0 °
Center (x,y) 0.0 0.0 mm

Fig. 1 Overview of the numerical simulation model

Fig. 2 shows the material flow during the individual stages of clinching joining two steel sheets, which was created using a 2D axisymmetric simulation using the finite element method. The flow of the joined sheets is analogous to the material deformation during the drawing of the sheet into a circular section.

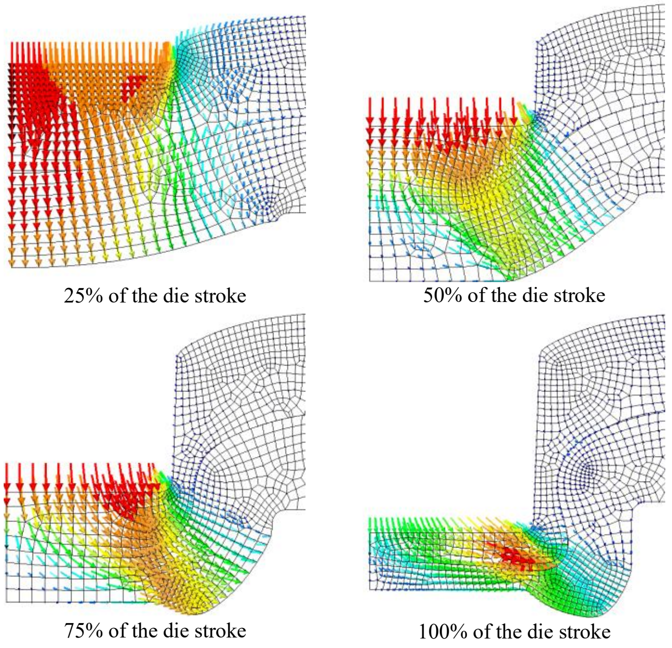

25% of the die stroke
50% of the die stroke
75% of the die stroke
100% of the die stroke

Fig. 2 Material flow in the cavity of the die during clinching

Joining process

The clinching joints were used to verify the results of numerical simulation. Clinching is a mechanical joining method used primarily for sheet metal components. It works by applying localized cold forming to produce a strong mechanical interlock, eliminating the need for additional fasteners (such as rivets or screws) or heat-based processes (like welding or brazing). The process depends on the plastic deformation properties of the materials being joined [10]. Clinching combines drawing and forming processes to achieve a mechanical interlock between steel sheets (**Fig. 3**).

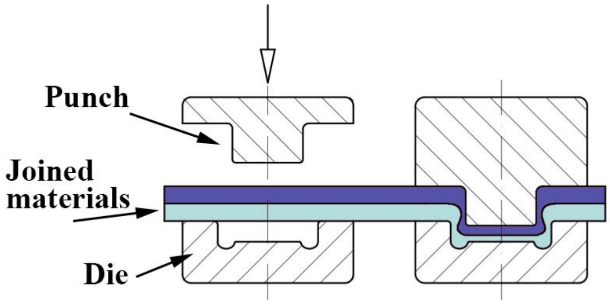


Fig. 3 Principle of mechanical joining by clinching

The clinching was performed by joining with a punch of Ø5 mm and a die of Ø8 mm.

Tensile test

The samples for mechanical joining using the clinching method were prepared in accordance with ISO 12996:2013: Mechanical joining – Destructive testing of joints – Specimen dimensions and test procedure for tensile shear testing of single joints. The steel sheets' surfaces were not cleaned before joining. The dimensions of the test specimen with a clinching joint are shown in **Fig. 4**. Tensile tests were performed under displacement-controlled conditions on the samples to evaluate the static behaviour of the joints and determine their ultimate tensile strength.

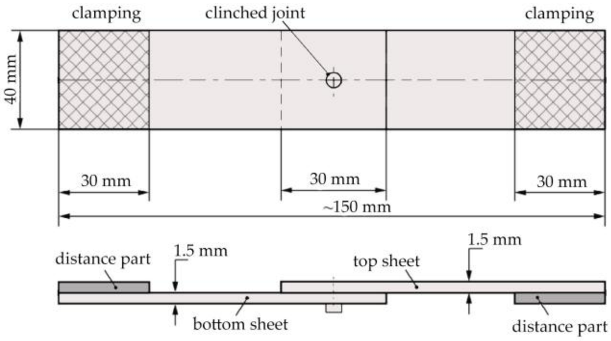


Fig. 4 Sample for the tensile test (according to ISO 12996:2013)

The tests were carried out using a TIRAtest 2300 metal strength testing machine, produced by VEB TIW Rauenstein, with a loading speed of 8 mm/min (**Fig. 5**). For the tensile test, 10 samples were used for each steel sheet.

Fig. 5 TIRAtest 2300 tensile test machine

Metallography

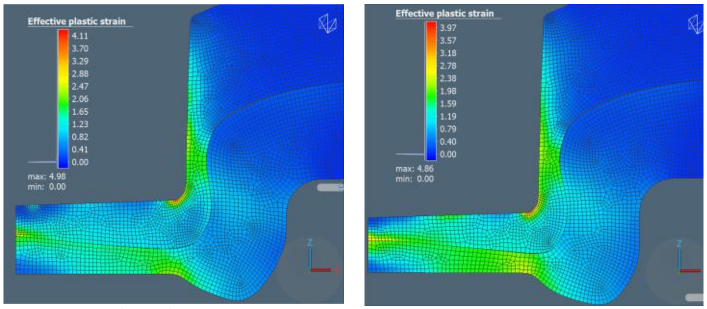
Metallographic analysis was also performed on the clinched joints to detect potential defects, including cracks, structural failures, or inadequate interlocking. Preparation of samples for metallographic observation involved grinding, polishing, and etching. The observations were carried out using a KEYENCE VHX-5000 digital light optical microscope (**Fig. 6**).

Fig. 6 Digital optical microscope KEYENCE VHX-5000

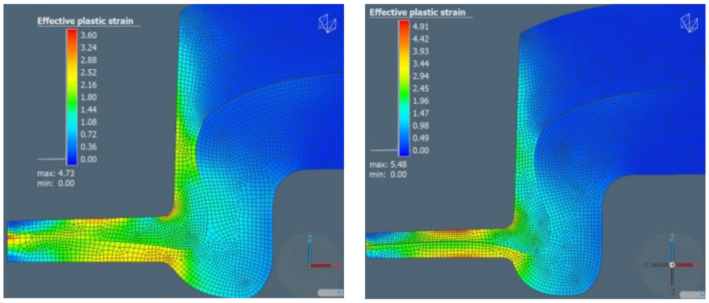
RESULTS

Results of FEM analysis

The results of the numerical simulation of HCT600X+Z sheets clinching showed that all used punch stroke settings led to the creation of a clinching joint without internal errors (**Fig. 7**). However, the interlock of the joint and the thickness of the bottom of the joint changed significantly. As the value of the punch stroke increases, the value of the interlocking of the joint increases and the thickness of the bottom of the joint decreases.

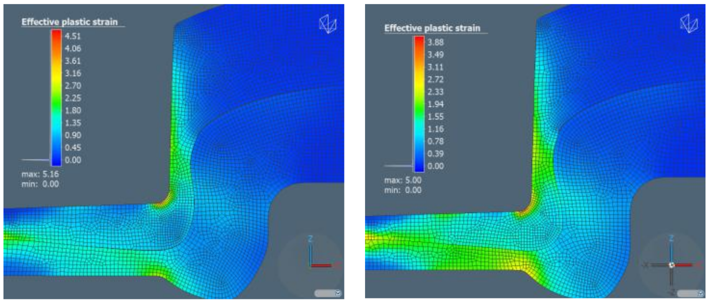


Punch stroke: 3.4 mm
Punch stroke: 3.6 mm

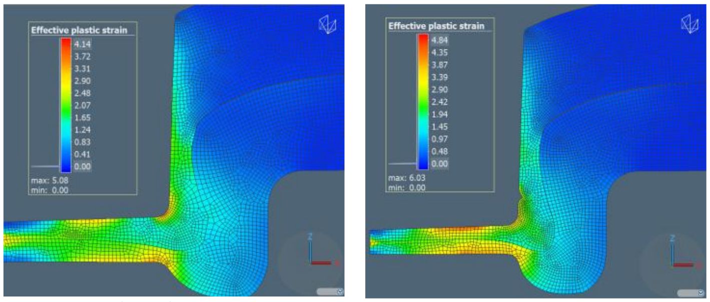


Punch stroke: 3.8 mm
Punch stroke: 4.0 mm

Fig. 7 Results of FEM analysis of clinching of HCT600X+Z



Punch stroke: 3.4 mm
Punch stroke: 3.6 mm



Punch stroke: 3.8 mm
Punch stroke: 4.0 mm

Fig. 8 Results of FEM analysis of clinching of HX420LAD+Z

Numerical simulation results of HX420LAD+Z steel sheets clinching showed similar results in terms of punch stroke settings used (**Fig. 8**). In this case, too, the formation of a clinching joint without internal defects was predicted. The interlocking of the joint and the thickness of the bottom of the joint vary significantly, as in the previous case. As the value of the punch stroke increases, the interlocking value increases and the thickness of the joint bottom decreases.

Load-displacement curves

Load-displacement curves of clinched joints on HCT600X+Z sheets showed a typical load response of a clinching joint (**Fig. 9**). The highest value of the loading force F_{max} was recorded when the punch stroke was set to 3.6 mm. Further higher values of the punch stroke setting 3.8 and 4.0 led to a decrease in the highest value of the loading force F_{max}. The most significant decrease in F_{max} was recorded at a punch stroke of 4.0 mm.

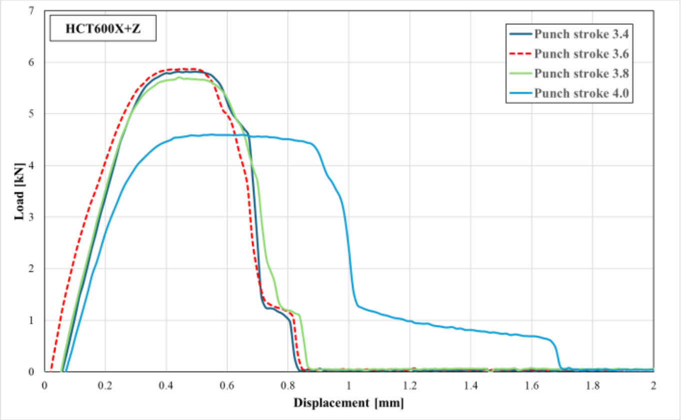


Fig. 9 Load-displacement curves of clinched joints made on HCT600X+Z steel sheets

The load–displacement curves of clinched joints in HX420LAD+Z sheets (Fig. 10) exhibited the typical behavior of a clinched joint, similar to HCT600X+Z steel sheets. The maximum loading force F_{max} was obtained at a punch stroke of 3.6 mm. When the punch stroke was increased to 3.8 and 4.0 mm, the maximum loading force F_{max} decreased.

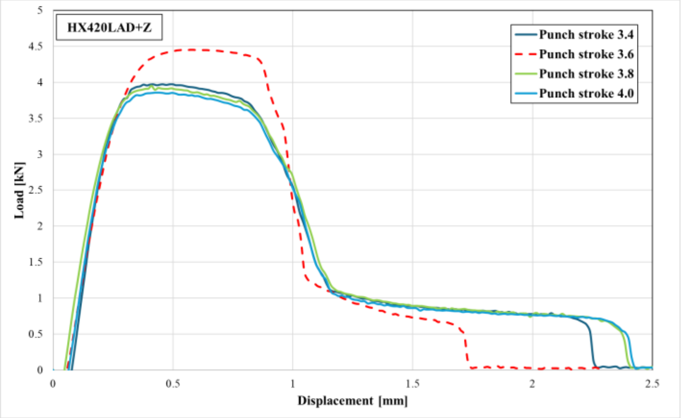


Fig. 10 Load-displacement curves of clinched joints made on HX420LAD+Z steel sheets

Metallographic observation

Figs 11 and 12 compare metallographic cross-sections of experimentally formed clinching joints with the results of FEM analysis of the clinching joint. Metallographic analysis of both investigated sheets HCT600X+Z and HX420LAD+Z confirmed the formation of a clinching joint without internal defects with a typical interlocking in the joint neck area.

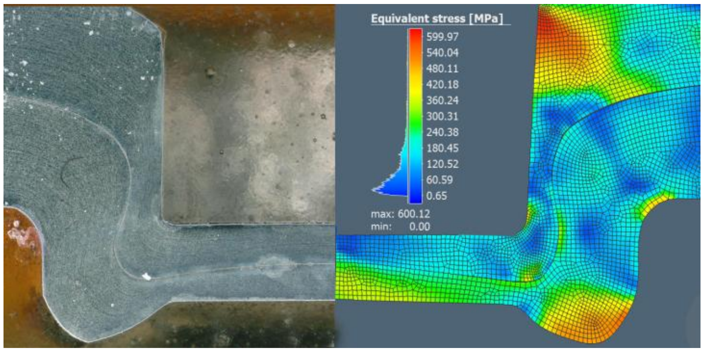


Fig. 11 Comparison of the real clinching process and the simulation result (HCT600X+Z, punch stroke 3.6 mm)

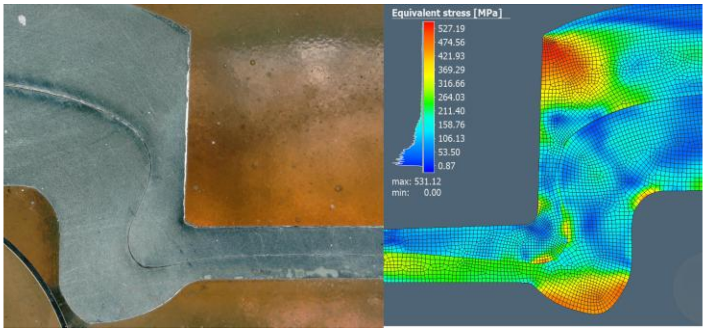


Fig. 12 Comparison of the real clinching process and the simulation result (HX420LAD+Z, punch stroke 3.6 mm)

CONCLUSION

Mechanical joining by the clinching method represents a suitable alternative to resistance spot welding for materials used in the production of automotive body structures. This technique enables the joining of sheet metals through localized cold forming, without the formation of heat-affected zones. In addition to this advantage, clinching offers several further benefits, including reduced energy consumption, shorter processing times, and improved environmental compatibility.

The clinching process for 1.5 mm thick sheets of high-strength steels HCT600X+Z and HX420LAD+Z was investigated and optimized in this study using FEM simulations in Simufact Forming. The simulations showed that all investigated values of the punch stroke led to the creation of a flawless joint, while with increasing stroke, mechanical interlocking increased and at the same time the thickness of the joint bottom decreased. Experimental tensile tests showed that the maximum load-bearing capacity of the joint, Fmax, was achieved at a punch stroke of 3.6 mm for both investigated materials; beyond this stroke, joint strength decreased. Metallographic analysis confirmed a very good match between the simulated joint shape and geometry and the formed joints, without internal defects.

Acknowledgements: The Authors are grateful for the support of experimental works by the project VEGA 1/0330/24. Funded by the EU Next Generation EU through the Recovery and Resilience Plan for Slovakia under the project No. 09I03-03-V04-00694.

REFERENCES

1. T. Kvackaj, J. Bidulská, R. Bidulský: Materials, 14(8), 2021, 1988. https://doi.org/10.3390/ma14081988
2. R. Kuziak, R. Kawalla, S. Waengler: Archives of Civil and Mechanical Engineering, 8(2), 2008, 103–117. https://doi.org/10.1016/S1644-9665(12)60197-6
3. F. Forouzan, M.A. Guitar, E.Vuorinen, F. Mücklich: Metals, 8(10), 2018, 747. https://doi.org/10.3390/met8100747
4. R. Tolouei, H. Titheridge: Transportation Research Part D: Transport and Environment, 14(6), 2009, 385–399. https://doi.org/10.1016/j.trd.2009.01.005
5. L. Gardyński, J. Caban, Jacek, D. Barta: Advances in Science and Technology Research Journal, 12, 2018, 181-187. https://doi.org/10.12913/22998624/92096
6. J. Galán, L. Samek, P. Verleysen, K. Verbeken, Y. Houbaert: Revista de Metalurgia, 48(2), 2012, 118–131. https://doi.org/10.3989/revmetalm.1158
7. A. Jabbar Hassan, B. Cheniti, B. Belkessa, T. Boukharouba, D. Miroud, N.E. Titouche: Acta Metallurgica Slovaca, 29(2), 2023, 88–92. https://doi.org/10.36547/ams.29.2.1802
8. J. Viňáš, Ľ. Kaščák, M. Greš: Open Engineering, 6(1), 2016, 504–510. https://doi.org/10.1515/eng-2016-0069
9. Y.B. Li, D.L Li, Z.Q. Lin, S.A. David, Z. Feng, W. Tang, Review: Science and Technology of Welding and Joining, 21(1), 2016, 59–74. https://doi.org/10.1179/1362171815Y.0000000059
10. H.G. Mohammed, T.L. Ginta, M. Mustapha: Materials Today: Proceedings, 46(4), 2021, 1640–1644. https://doi.org/10.1016/j.matpr.2020.07.258
11. S. Baruah, I. V. Singh: Finite Elements in Analysis and Design, 226, 2023, 226, 104024. https://doi.org/10.1016/j.finel.2023.104024
12. W. Dai, D. Li, D. Tang, Q. Jiang, D. Wang, H. Wang, Y. Peng: Journal of Manufacturing Processes, 62, 2021, 262–274. https://doi.org/10.1016/j.jmapro.2020.12.015
13. Ľ. Kaščák, J. Mucha, J. Varga, J. Slota, E. Kaščáková: Acta Metallurgica Slovaca, 30(4), 2024, 188-191. https://doi.org/10.36547/ams.30.4.2106
14. G. Meschut, V. Janzen, T. Olfermann: Journal of Materials Engineering and Performance, 23, 2014, 1515–1523. https://doi.org/10.1007/s11665-014-0962-3
15. J. Richter, M. Kuhtz, A. Hornig, M. Harhash, H. Palkowski, M. Gude: Metals, 11(5), 2021, 1-19. https://doi.org/10.3390/met11050818
16. X. Ren, C. Chen: Journal of Materials Research and Technology, 25, 2023, 5650-5662. https://doi.org/10.1016/j.jmrt.2023.06.242
17. L. Lei, X. He, T. Yu, B. Xing: Thin-Walled Structures, 144, 2019, 106281. https://doi.org/10.1016/j.tws.2019.106281
18. X. He: Science and Technology of Advanced Materials, 18(1), 2017, 381-405. https://doi.org/10.1080/14686996.2017.1320930
19. H. Peng, C. Chen, X. Ren, X. Ran, X. Gao: Thin-Walled Structures, 169, 2021, 1-9. https://doi.org/10.1016/j.tws.2021.108289
20. J. Mucha, Ł. Boda, W. Witkowski: International Journal of Precision Engineering and Manufacturing-Green Technology, 11, 2024, 1475-1499. https://doi.org/10.1007/s40684-024-00612-0
21. L. Lei, Y. Shi, M. Yan, Ch. Song, Z. Zhao: Engineering Failure Analysis, 158, 2024, 108001. https://doi.org/10.1016/j.engfailanal.2024.108001
22. C. Steinfelder, D. Rempel, A. Brosius: Journal of Advanced Joining Processes, 10, 2024, 1-8. https://doi.org/10.1016/j.jajp.2024.100263
23. L. Fu, S. Zhang, P. Qiu, H. Xiao, B. Deng, X. Lu: Metals, 14, 2024, 767. https://doi.org/10.3390/met14070767
24. Ch. R. Bielak, M. Böhnke , M. Bobbert, G. Meschut: Proceedings of the Institution of Mechanical Engineers, Part L. 236(6), 2022, 1225-1235. https://doi.org/10.1177/14644207221093468
25. Ľ. Kaščák, J. Varga, J. Bidulská, R. Bidulský, M.A. Grande: Acta Metallurgica Slovaca, 99(2), 2023, 113-118. https://doi.org/10.36547/ams.29.2.1846
26. T. Balawender, T. Sadowski, P. Golewski: Computational Materials Science, 64, 2012, 270-272. https://doi.org/10.1016/j.commatsci.2012.05.014
27. Varga et al.: Applied Sciences, 12 (20), 2022, 1-22. https://doi.org/10.3390/app122010638
28. Y. Liu, Y. Dai, X. Liu, W. Zhuang: Materials Today Communications, 44, 2025, 111942. https://doi.org/10.1016/j.mtcomm.2025.111942