UNIVERSITATEA LUCIAN BLAGA DIN SIBIU

Doctoral school: Engineering Sciences and Mathematics

Doctoral field: Industrial Engineering

STUDIES AND RESEARCH ON THE HARDFACING OF METAL SHEETS BY MEANS OF WELDING

ABSTRACT

Doctoral student:

Fineas MORARIU

Doctoral supervisor:

Prof. Sever-Gabriel RACZ

SIBIU 2025

Contents

Introduction

Resistance to abrasive wear is essential for metal parts used in demanding industrial conditions, ensuring their durability and efficiency. Abrasive wear occurs when metal materials interact with abrasive particles, causing progressive damage that can affect the structural integrity and functionality of the parts. The material and proper treatment of parts are important for increasing abrasive wear resistance. Martensitic steels, such as those in the *Hardox* series, and *Hadfield* steels are frequently used due to their superior abrasion and impact resistance properties, making them ideal for applications in severe wear conditions [1]. Surface improvement processes, such as cladding, are also important as they help extend the service life of metal components by protecting them against abrasive wear with a wear-resistant barrier layer [2].

Adapting and optimising manufacturing processes using modern technologies also allows for the precise and efficient application of the treatments needed to maximise wear resistance. This not only improves the performance of the machines these components are part of, but also contributes to the sustainability of industrial processes by reducing material waste [3].

Thus, combining a thorough understanding of abrasive wear with the implementation of advanced technological solutions and appropriate treatments becomes a key factor in the advancement of materials engineering. The synergy of these concepts also contributes to the efficient use of resources and the sustainability of industrial processes.

In the context of continuous expansion and improvement of technological processes at the company level, the selection of the thickness and format of the welding sheet is not random, but is the result of two decades of experience accumulated in the metallurgical industry in Romania. Over the years, the company has achieved an impressive production volume, reaching 15,000 sheets and exceeding 60,000 [m²] of welded clad sheet metal. These figures highlight the company's organisational and technical capabilities, as well as the need for continuous process optimisation in order to maintain a high level of quality and efficiency.

Over the years, analysis of monthly production, which averages over 310 [m²] of clad sheet, has shown that most clad sheets are 3000 x 1500 [mm x mm], with a base material thickness of 6 [mm] and a coating thickness of 3 [mm]. This not only reflects market preferences, but also the efficiency of the production process adapted to this specific format. The chosen size and thickness allow for reduced production costs, maximised material utilisation and improved weld quality, which are important aspects for maintaining competitiveness in today's dynamic market.

In this context, the topic of this paper – *Studies and research on metal sheet cladding by welding* – was chosen as a direct response to the need to identify and optimise the technological parameters involved in the cladding process, with the ultimate goal of improving the performance of welded clad metal sheets under abrasive wear conditions.

The paper aims to investigate the influence of process factors on the chemical composition, microstructure and mechanical properties of the deposited layer, in order to establish an optimal welding technology regime. Correlating these experimental results with the final performance of the clad layer aims to obtain solutions that can be directly applied in the production flow, with real benefits for the durability and efficiency of the manufactured parts.

Thus, the research is aligned with current industry concerns regarding cost reduction, product quality improvement and manufacturing process sustainability through the integrated use of technological resources.

The research presented in this doctoral thesis was developed in the context of a real need identified in the industrial company where the author works, namely the optimisation of the metal sheet plating process by welding. This topic was chosen in line with the realities of production, where sheet metal cladding is currently carried out in order to improve abrasive wear resistance and extend the service life of metal components subjected to severe stresses.

The diagram in Figure I shows the logical course of the research, from the analysis of the current state and the definition of the experimental framework to the complete evaluation of the mechanical, structural and functional properties of the plated layers, ending with the general conclusions.

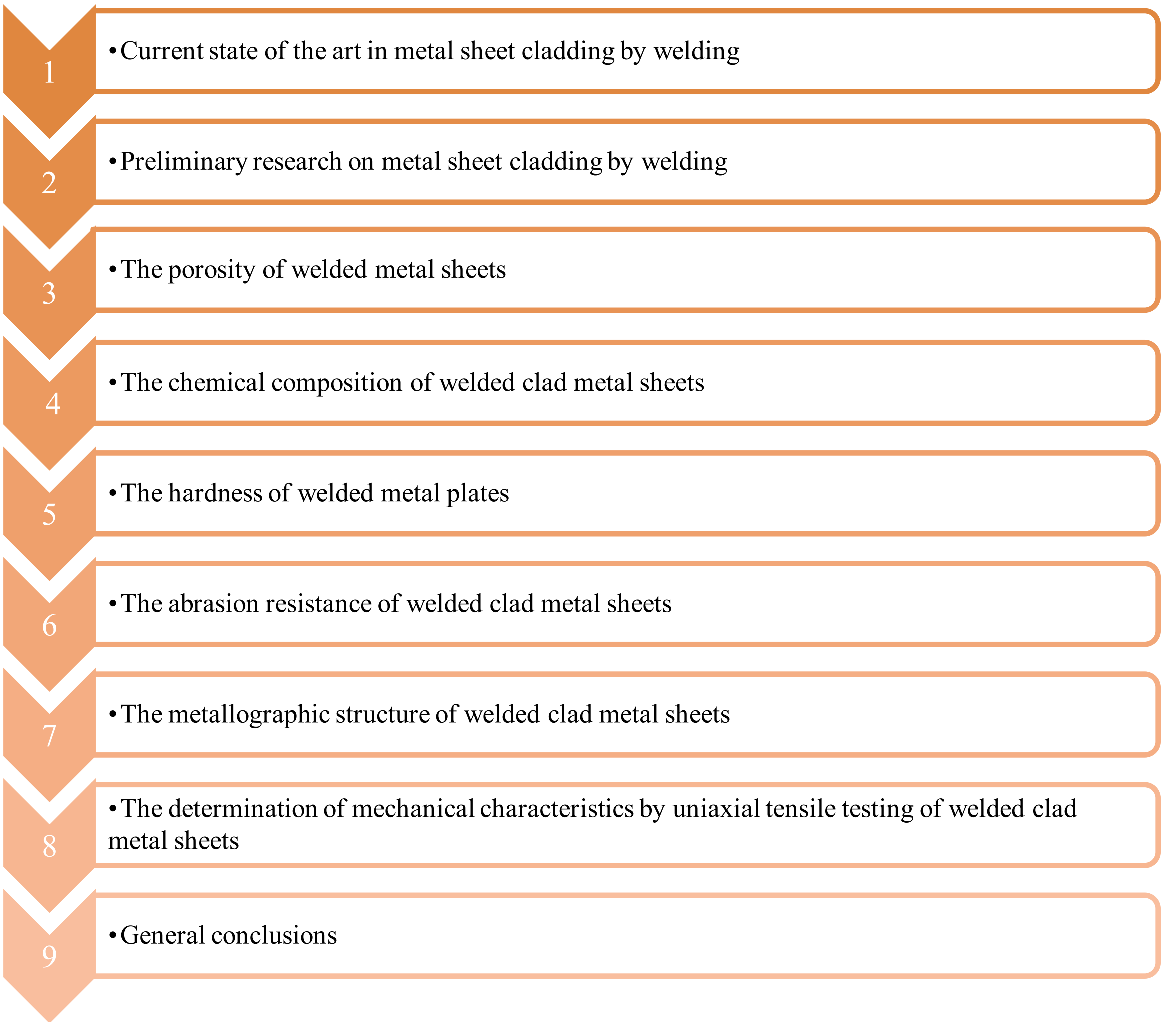

Fig. I Stages of research on metal sheet cladding by welding

The bibliographic documentation part allowed the identification of the main current research directions on self-shielded flux-cored arc welding (FCAW-S), as well as the materials used in such applications, both in international literature and in national research. The bibliometric analysis highlighted the constant interest in optimising the technological parameters of the welding process and their impact on the structure and properties of the deposited layer. This stage built the basis for formulating the general and specific objectives of the paper, substantiating the need for an experimental approach.

Following the chapter on the current state of the art, the research direction was structured in a logical and coherent manner, reflecting the scientific approach adopted:

- Chapter 2 is dedicated to preliminary studies, presenting details on the welding cladding process, the materials used (base material and filler wire), the justification for the choice of the technological parameters pursued, and the experimental design adopted. The

Taguchi method was used, accompanied by a robust statistical approach, designed to identify the influence of each parameter on the properties of the deposited layer.

- Chapters 3–7 are dedicated to the experimental stages, each specifically analysing a critical aspect of the behaviour of welded clad plates:
  - Chapter 3: Porosity evaluation to analyse internal defects generated by variations in welding parameters;
  - Chapter 4: Chemical composition analysis to correlate the concentrations of alloying elements (Cr, Mn, Ni, Ti) with the welding parameters and the type of base material;
  - Chapter 5: Hardness measurements, which evaluate the local strength of the deposited layer in relation to the welding parameters and chemical composition;
  - Chapter 6: Abrasive wear tests (ASTM G65), which deal with the behaviour of the coating under abrasive wear, through tests carried out under controlled conditions designed to simulate industrial operating conditions;
  - Chapter 7: Microstructure study by metallographic analysis to identify the phases formed and the thermal influence generated by the welding process;
  - Chapter 8: Uniaxial tensile test to verify the influence of deposition on the mechanical behaviour of clad plates.
- Chapter 9 is dedicated to general conclusions, summarising the research results. It also presents personal contributions and proposes future research directions, with an emphasis on the industrial implementation of the results obtained and the extension of the study to other cladding materials or technologies.

Thus, the entire scientific approach aims to correlate the influence of the technological parameters of welding cladding with the physical, mechanical and structural properties of the deposited layer in a manner that is directly applicable in an industrial context. Optimising the cladding process is not only a scientific objective, but also a practical one, aimed at increasing efficiency and competitiveness in the production of welded clad metal sheets.

1. Current status of metal sheet cladding by welding

The structure of Chapter 1 has allowed us to outline a coherent conceptual and practical framework for welding cladding, starting from a bibliometric analysis of recent research in the field. The results of this analysis revealed the dominant areas of scientific interest, as well as a significant focus on process optimisation, increasing the reliability of the deposited layer and extending the applicability of advanced materials. The integration of these data provided a solid basis for choosing the topic and defining the technical objectives.

Next, a classification of cladding processes was carried out, highlighting the relationship between the energy source used (electric arc, laser, electron beam) and the specificity of the targeted industrial applications. The thermal implications of each process, the degree of dilution, the thermally affected area and the impact on the structure of the plated layer were detailed. This stage demonstrated the importance of adapting the process to the functional requirements of the components.

The section on base materials and additives highlighted the role of chemical and structural compatibility in achieving durable adhesion without fusion defects or the formation of brittle phases. The bidirectional nature of the influence was emphasised: the base material dictates the plating conditions, and the additive material determines the final performance of the deposited layer.

By classifying the types of coatings (hard, functional, corrosion-resistant or high-temperature resistant), the areas of application were defined and a bridge was built between the operating requirements and the technological selection. This correlation supports the idea that coating should be approached as a customised engineering solution, not as a universal process.

Overall, the chapter has built the theoretical and technological foundation necessary for understanding the subsequent stages of the work, providing an overview of the critical variables involved in the welding cladding process, as well as the directions for technological optimisation in relation to new industrial requirements.

2. Preliminary research on metal sheet cladding by welding

The second chapter outlined the general direction of the research by clearly presenting the technological context of metal sheet cladding by welding. Starting from industrial requirements, the types of materials used, the characteristics of the FCAW-S welding process and the equipment involved were analysed in order to understand and define the actual conditions of the application.

The structure of the experiment was then established by selecting the relevant variables and constant parameters and choosing an appropriate statistical investigation method. Factorial planning and the application of the Taguchi method allowed the tests to be organised efficiently, providing the necessary conditions for exploring the relationships between the technological parameters and the quality of the deposited layers.

3. Porosity of welded clad metal sheets

The research in Chapter 3 comprehensively addressed the issue of porosity in welded metal coatings, starting with a theoretical analysis of the mechanisms of pore formation and culminating in a complex experimental evaluation supported by quantitative methods and statistical modelling.

In the first stage, the concept of porosity was defined and the usual types of defects were presented, accompanied by a detailed classification according to origin, morphology and distribution. This part laid the foundations for understanding the physical and chemical phenomena responsible for the appearance of pores in the deposited layer.

To characterise porosity, various experimental methods, both non-destructive and destructive, were presented to cover the entire range of pore sizes and types. The method was selected to correspond to the specific characteristics of the welded samples.

The methodology applied included controlled cutting of samples, 3D scanning to determine average thickness, weighing and data processing in specialised software, allowing a correlation between actual mass, effective volume and porosity estimation. This methodological framework allowed not only the quantification of porosity, but also the indirect validation of deposit homogeneity.

Statistical analysis (GLM – ANOVA and multiple regression) allowed the quantification of the significance of each welding parameter on the estimated porosity. It was demonstrated that the number of layers and the applied voltage have the strongest impact, followed by the wire speed and the nozzle height. The substrate material had a marginal but statistically significant effect.

The interpretation of the regression coefficients provided a clear picture of the direction of each factor's influence: the application of a single layer (L1), a higher voltage (27 V) and a low wire speed (3.2 mm/s) proved to be the optimal conditions for obtaining a plated layer with minimal porosity.

The results of the experiments support the statistical conclusions, highlighting the superior behaviour of the M2–L1 configuration, which generated the lowest porosity values under optimal welding conditions. The chemical composition of the S355MC material and the dilution control favoured a homogeneous deposition with a compact microstructure. In contrast, the M1–L2 configuration maintained the porosity high, regardless of the parameters due to the influence of reheating and the limited degassing capacity of the S235JR+N material.

The influence of dilution was also analysed in the context of the process, highlighting the inverse relationship between the degree of dilution and porosity. Increased dilution contributes to the efficient removal of gases, favouring the achievement of a compact layer with no visible voids.

For the cladding of metal sheets by welding, the final thickness of the added layer influences both the service life and the porosity. A greater thickness (6+3+3 [mm]) can increase porosity due to the accumulation of pores between layers, but ensures a longer service life due to additional protection against corrosion and wear.

Therefore, the results obtained and presented in this chapter have experimentally validated an integrated quantitative approach for assessing porosity in weld-clad metal sheets and provided a solid predictive framework for optimising process parameters with the aim of reducing internal defects and increasing the reliability of the protective layer.

4. Chemical composition of weld-clad metal sheets

This chapter addressed the influence of chemical composition on welded clad sheets, highlighting the role of the base material, the filler material and the wire flux in obtaining high-performance deposited layers. The interaction between these components, the influence of the composition on the thermal and metallurgical processes in the weld pool, and how the welding parameters influence the final microstructure were analysed.

The experimental analysis, performed using an XRF spectrometer, focused on elements such as Cr, Mn, Ni and Ti. For chromium, the direct influence of voltage, wire height and feed rate on dilution was highlighted. Average voltages (23–25 [V]), a stick-out of 25 [mm] and a speed of 3.6–4 [m]/[min] allowed the production of Cr-rich layers with high overall hardness.

In the case of manganese, it was observed that the nozzle height had the greatest impact on the composition. Intermediate values (25 [mm]) allowed for a reduction in evaporation losses and maintained a stable Mn level. Wire voltage and speed had a lesser influence but required adjustment depending on the desired thermal regime.

For Ni and Ti, concentrations were low and variations were attributed to dilution or oxidation. Although no detailed analysis was performed, it was found that strict arc control can contribute to the retention of these elements.

The results show that careful adjustment of the welding parameters allows control of the chemical composition and dilution. A moderate regime is recommended to maintain optimal concentrations of alloying elements and to avoid structural defects. These conclusions may contribute to improving the process of cladding metal sheets by welding using the FCAW-S process, in order to obtain coatings suitable for applications requiring superior strength and durability properties.

5. Hardness of weld-clad metal sheets

The research in this chapter investigated the influence of chemical composition, welding parameters and thermal conditions on the hardness of weld-clad sheets, with the main objective of optimising the cladding process parameters to obtain high and uniform overall hardness. Hardness was measured using the Rockwell method, using the INSIZE ISH-BRV hardness tester, on 36 samples clad with one or two layers.

The analysis showed that the hardness of the deposited layer is significantly influenced by the material used, the number of layers applied, the welding voltage and the nozzle height. Of these factors, the M2 material and the two-layer deposition (L2) led to the highest overall hardness values, due to the reduction in dilution and the maintenance of a high concentration of alloying elements such as Cr. In contrast, the wire speed had a reduced effect on the average hardness.

It was observed that low voltage and a high nozzle height favour a fine, poorly diluted structure with high hardness. In addition, the application of the second layer had a beneficial effect on uniformity and hardness increase, compensating for the dilution losses of the first layer. If the main objective is to obtain high hardness, then it is recommended to use parameters that reduce dilution and allow the formation of stable hard phases.

At the same time, the analysis highlighted the interaction between Cr content, porosity and overall hardness, indicating that maximum hardness is not sufficient for the performance of the layer in service if porosity is increased. Thus, the optimisation of hardness must be accompanied by control of porosity and chemical composition, and for this, a balance between homogeneity and structural integrity is essential.

6. Abrasion resistance of weld-clad metal sheets

The research in Chapter 6 aimed to evaluate the abrasive wear resistance of FCAW-S welded clad metal sheets, completing the analysis of the mechanical and microstructural properties of the deposited layers. The tests were performed according to the standard ASTM

G65 – Procedure A, and the results were interpreted from the perspective of the influence of process parameters and layer characteristics on material loss.

The analysis showed that the main factors influencing wear are arc voltage [V], nozzle height [mm] and wire speed [m/min], while the filler material and number of layers (L) had a statistically lower influence. However, the two-layer samples (L2) and material M2 generally showed better abrasion resistance due to their more stable microstructure, reduced dilution and uniform distribution of hard phases.

Correlating the mass loss results with hardness, porosity and chemical composition, it was observed that high hardness does not automatically guarantee increased abrasive wear resistance. Factors such as carbide distribution, layer density and the presence of pores significantly influenced abrasion performance. Samples with a dense microstructure, well-distributed Cr carbides and low porosity content showed the best results.

The optimal process for minimising abrasive wear was identified as a combination of 27 [V] voltage, 20 [mm] H distance and 4 [m/min] wire speed.

Following multi-criteria optimisation using Minitab, an optimal configuration of process factors was identified that ensures a balance between the analysed criteria. The score D = 0.88 confirms that a high level of simultaneous satisfaction of the objectives of minimising mass loss and porosity, as well as maximising overall hardness and chromium concentration, has been achieved. Estimated values for the response variables at the optimum point are Cr [%]=18.71, Dg [HRC]=64.16, P [%]=0.81, Δm [g]=0.12.

The results highlight the importance of controlling welding parameters and chemical composition in order to obtain a high-performance plated layer in abrasive environments. It is also recommended to optimise the process parameters not only according to the response size (hardness [HRC]), but also in relation to structural homogeneity, hard phase content and defect level, in order to ensure real and durable resistance to abrasive wear.

7. Metallographic structure of welded clad metal sheets

In Chapter 7, the research focused on a detailed analysis of the metallographic structure of layers deposited by the FCAW-S process, in order to correlate the microstructure with the mechanical and tribological properties of the layers applied to carbon steel (S235JR+N) and high-strength steel (S355MC) sheets. The research focused on evaluating the influence of chemical composition, welding regime and cooling rate on the formation of metal phases, on the adhesion of the deposited layer to the substrate and on the behaviour under abrasive wear.

The deposition variants M1–L1, M1–L2, M2–L1 and M2–L2 were analysed, and for each of these test specimens with extreme (positive and negative) performance were identified based on parameters such as hardness, porosity, Cr content and mass loss through abrasive wear. Following microstructural analyses, the following relevant aspects were highlighted:

- The transition zone between the base material and the deposited layer plays a critical role in the overall behaviour of the layer, influencing adhesion, local hardness and resistance to mechanical stress. The progressive transitions of the metal phases and the formation of Cr carbides indicate good metallurgical fusion.
- The presence of martensite was consistently identified in the upper areas of the deposited layer as a result of the rapid cooling specific to the FCAW-S process. This phase contributed to the increase in layer hardness, but also to local embrittlement, depending on the distribution of carbides and porosity.
- Cr carbides proved to be essential in improving abrasive wear resistance. It was found that their uniform distribution, obtained under optimised welding conditions, ensures a homogeneous microstructure and superior performance of the deposited layer.
- High dilution and maintaining a short distance between the welding nozzle and the substrate have been confirmed as factors favouring the achievement of a fine, dense and abrasion-resistant structure. This has been validated in particular for the S20, S46 and S102 test pieces.
- Although high hardness values were obtained in some cases (S62, S34) due to the increased Cr content, the uneven distribution of alloying elements and the presence of porosity led to poor abrasive wear performance, emphasising that high hardness does not guarantee adequate performance in service.

Metallographic analysis showed that the microstructure of the deposited layer is deeply influenced by the welding regime and the composition of the base and additive materials, and that a fine, homogeneous microstructure with uniform carbide distribution and low porosity is the desired solution for obtaining mechanically and tribologically efficient layers.

8. Determination of mechanical characteristics by uniaxial tensile testing of welded clad metal sheets

The research presented in the eighth chapter aims to compare the results of the uniaxial tensile behaviour of the base material, S355MC, and the welded samples. The analysis showed a significant decrease in the post-weld mechanical properties, regardless of the configuration chosen. It is clear that the base material, unaffected by welding, retains the highest levels of tensile strength and yield strength, as well as superior ductility, illustrating the negative impact of the welding process on the structural integrity of the steel.

Comparing the single-layer welded samples with the double-layer welded samples, a marked decrease in mechanical strength is observed in the latter. This phenomenon can be attributed to the accumulation of residual stresses and deeper alteration of the microstructure resulting from repeated heat application. The welding process, by its nature, induces changes in the structure of the metal, negatively affecting its mechanical properties.

With regard to the orientation of the weld rows relative to the direction of pull, the results suggest that 0° orientations tend to exhibit significantly higher mechanical performance compared to those at 45° or 90°. This indicates that aligning the weld parallel to the direction of the applied tensile force can help minimise the negative impact of welding on the strength of clad plates. Welding perpendicular to the direction of traction shows the greatest changes and, consequently, the greatest decrease in mechanical properties, due to the concentration of stresses at the interface between the layers and the base material, which facilitates the initiation and propagation of cracks under mechanical loads.

Metal plate cladding by welding can offer specific benefits, such as resistance to abrasive wear by increasing hardness, but at the same time it requires optimisation to minimise the negative impact on structural properties. Thus, the appropriate selection of welding parameters together with the orientation of the weld beads in relation to the direction of force and the number of layers are important to match the mechanical characteristics with the functional requirements of the welded components. Future research aims to analyse different welding techniques and post-processing treatments that can improve the ductility and tensile strength of abrasion-resistant sheets, ensuring both their functionality and durability in critical applications.

9. General conclusions

Based on the results obtained from the theoretical and experimental research on FCAW-S welded clad metal sheets, presented in detail in the previous chapters, the following general conclusions can be drawn:

- Sheet metal cladding by welding is an effective technological solution for improving durability in industrial applications subject to wear;
- Weld-clad metal sheets are widely used in industries such as concrete, asphalt, ceramics, agriculture and the energy sector, where increased resistance to abrasive wear is required;

- The main stages of the technological process for obtaining clad metal sheets include cladding (application of the additive layer), cutting to the desired dimensions, roll forming to adapt the shape, and final assembly of the product;
- From a sustainability perspective, recent research supports the use of deposition methods that reduce material losses and optimise energy consumption;
- Recent studies highlight the importance of controlling technological parameters (voltage, nozzle height, wire speed) on the quality of the deposited layer, influencing dilution, porosity, hardness and microstructure;
- In industrial applications in abrasive environments, FCAW-S welding of metal sheets is an effective method for obtaining hard coatings;
- The appropriate choice of the number of layers and the filler material can improve performance in service and reduce wear in abrasive environments;
- The number of layers influences the mechanical characteristics of the coated sheets; as the number of layers increases, both the mechanical strength and deformability decrease, but the abrasive wear resistance of the surface layer improves;
- The porosity of the deposited layer was evaluated as a critical parameter in determining weld quality, having a direct impact on durability and abrasive wear behaviour.
- Double-coated samples showed higher porosity, but also a distribution of pores on the surface of the second layer, while single-coated samples showed deep and uneven pores, with a potentially negative effect on the integrity of the layer.
- A correlation was found between welding parameters and porosity: the nozzle height and wire speed significantly influence the quantity and size of the pores formed.
- Controlling porosity by adjusting the technological parameters is important for obtaining a dense microstructure without discontinuities, but also for reducing other deposition defects, such as inclusions, slag formation or incomplete fusion between layers;
- The study highlighted the presence of hard phases (Cr carbides) distributed differently depending on the thermal regime applied, with well-defined eutectic formations in the M2-L2 coatings;
- The two-layer coatings had a more refined microstructure and better homogeneity due to reduced dilution in the upper layer;
- The control of parameters (U, H, VS) allowed the generation of fine-grained microstructures, favourable to hardness and abrasion resistance;

- The chemical composition of the additive significantly influences the microstructure of the deposited layer;
- Chromium contributes to the formation of hard phases, increasing hardness and abrasion resistance;
- Samples plated with M2 had a higher Cr content, explaining their superior performance in hardness tests;
- High dilution in L1 led to a decrease in the concentration of alloying elements, while L2 allowed the nominal composition of the wire to be maintained on the surface;
- Welding process parameters (voltage, nozzle height, wire speed) influence the dilution level and the resulting microstructure;
- Low voltage and high nozzle height favour the formation of a hard structure with low dilution;
- The number of deposited layers influences both the overall hardness and the abrasive wear behaviour;
- Samples coated with two layers showed more uniform hardness by reducing the influence of the substrate on the functional layer.
- A significant influence of the welding parameters on the overall hardness was observed: the nozzle height (H) and voltage (U) had the greatest impact.
- The M2-L2 samples reached maximum hardness values (> 68 [HRC]), while maintaining good uniformity between the base and the top of the layer – $\Delta D < 3$ [HRC].
- The study highlighted the need for a balance between hardness and homogeneity in order to avoid a decrease in the toughness of the material and the appearance of brittleness under stress conditions.
- The abrasive wear resistance determined by the ASTM G65 test is correlated with hardness, but is also affected by porosity and the quality of the bond between the layer and the substrate.
- Materials with medium and well-distributed carbides and a dense microstructure had the lowest volumetric wear rate [mm^3/m];
- The correlation between hardness, chemical composition, porosity and microstructure confirmed that abrasion resistance is the synergistic result of all these factors;
- Statistical analysis (ANOVA, GLM models) validated the significant influence of welding parameters on hardness and wear, confirming the robustness of the experimental models used;

- Multi-criteria optimisation of the process was achieved by identifying the parametric combination: material M2, two layers (L1), voltage 27 [V], nozzle height 20 [mm], wire speed 4.0 [m/min], favourable for maximising hardness and minimising mass loss through abrasion.
- The results obtained support the idea that the optimisation of welding parameters has an impact not only on hardness and abrasive wear, but also on mechanical characteristics.
- Uniaxial tensile testing allowed the mechanical characteristics of the clad plates to be evaluated, with a focus on the influence of cladding on tensile strength and deformability;
- Comparison of the mechanical characteristics of FCAW-S welded clad plates with S235 and S355 base materials revealed significant differences between them, demonstrating that the substrate influences the mechanical behaviour of welded clad plates.

Personal contributions

- Extensive documentation based on over 180 relevant scientific sources, which substantiates the results and contributes to positioning the work in the national and international context of studies on abrasion-resistant clad materials;
- Development of a complete factorial experimental plan, which allowed the systematic investigation of the influence of five parameters (voltage [V], nozzle height [mm], wire speed [m/min], filler material and number of layers) on the properties of the clad layer;
- Design of a coherent experimental methodology with clear, reproducible and adaptable steps for other types of materials or test conditions, providing a solid basis for further research;
- Integrated use of specialised softwares: Minitab (ANOVA, GLM), Excel (data processing), Gephi (graphical visualisation) and Zeiss Inspect (3D analysis) for interpretation of experimental results;
- Application of 3D scanning methods to determine the porosity of the plated layer and correlate it with volumetric wear;
- Proposing and applying a proprietary method for calculating the overall hardness (Dg) and the difference in hardness between the base and the tip (ΔD) as indicators of the homogeneity of the layer and its resistance potential manifested during the abrasive wear phenomenon;

- Adaptation of the ASTM G65 test for multi-layered materials by integrating an adjusted calculation of volume loss and reporting it in relation to the specific density of the material, which allowed for a comparable, rigorous evaluation aligned with the standards in the literature.
- Integration and multidisciplinary correlation between microstructural analysis, hardness, porosity, chemical composition and abrasive wear behaviour, providing a holistic view of the performance of FCAW-S welded cladding materials;
- Proposal of a multi-criteria optimisation model (hardness – abrasive wear – porosity – composition), which can be used in industry for rapid adjustment of parameters according to application requirements;
- Identification and validation of the optimal welding configuration representing a favourable ratio between hardness, homogeneity, adhesion and minimum abrasive wear: material M2, two layers (L1), U is 27 [V], H is 20 [mm], and VS is 4.0 [m/min];
- Application of statistical model validation criteria (R^2, adjusted R^2 and predictive R^2), with values above 94 [%], demonstrating the robustness of the conclusions and the reproducibility of the experimental results.

Future research directions

- Extension of abrasive wear tests by introducing tests in a humid environment (ASTM G105) or under repeated impact conditions to simulate real industrial applications;
- Analysis of behaviour at high temperatures through hot abrasive wear tests to evaluate the stability of hard phases under thermal conditions;
- Application of post-welding treatments, such as thermal or cryogenic treatments, to refine the microstructure and increase the hardness/toughness of the deposited layer;
- Use of additives with complex compositions (Fe-Cr-Nb-B-Ti) or hybridised powders to obtain multiphase layers with superior performance;
- Numerical modelling (FEM/CFD) of the welding and solidification process to simulate temperature distribution, dilution and defect formation, with a view to reducing physical experiments;
- Investigation of the behaviour of clad sheets under cold plastic deformation by rolling;
- Studies of behaviour in industrial use (agricultural machinery, crushers, mining equipment) to validate the durability of materials under real working conditions;

- Investigation of hybrid cladding, by combining two different additives or technological stages, to obtain layers with gradual functional properties and improved performance under abrasive wear.

10. Bibliography

1. Zemlik, M., et al., *Comparison of Abrasive Wear Resistance of Hardox Steel and Hadfield Cast Steel.* Applied Sciences, 2024.**14** (23): p. 11141.
2. Szala, M., *Cavitation Erosion, Abrasive and Sliding Wear Behaviour of Metal-Based Structures.* Metals, 2022.**12** (3): p. 373.
3. Jankauskas, V. and R. Skirkus, *Development and Testing of Materials with Reduced Wear by Fixed Abrasive.* Key Engineering Materials, 2012.**527** .DOI: 10.4028/www.scientific.net/KEM.527.229.
4. Świerczyńska, A., et al., *Exploring the trends in flux-cored arc welding: scientometric analysis approach.* The International Journal of Advanced Manufacturing Technology, 2024.**130** (1): p. 87-110.DOI: 10.1007/s00170-023-12682-6.
5. Ghanad, A., *An Overview of Quantitative Research Methods.* INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH AND ANALYSIS, 2023.**06** .DOI: 10.47191/ijmra/v6-i8-52.
6. Rusu, D.-M., S.-D. Mândru, C.-M. Biriș, O.-L. Petrașcu, F. Morariu, A. Ianosi-Andreeva-Dimitrova, *Soft Robotics: A Systematic Review and Bibliometric Analysis.* Micromachines, 2023.**14** (2): p. 359.
7. Mishra, R., P. De, and N. Kumar, *Friction Stir Welding and Processing: Science and Engineering.* 2005.DOI: 10.1007/978-3-319-07043-8.
8. Goldak, J.A., A.P. Chakravarti, and M. Bibby, *A new finite element model for welding heat sources.* Metallurgical Transactions B, 1984.**15** : p. 299-305.
9. Nandan, R., T. Debroy, and H. Bhadeshia, *Recent advances in friction-stir welding – Process, weldment structure and properties.* Progress in Materials Science, 2008.**53** : p. 980-1023.DOI: 10.1016/j.pmatsci.2008.05.001.
10. Cai, W., et al., *Self-limited plasmonic welding of silver nanowire junctions.* Nature materials, 2012.**11** : p. 241-9.DOI: 10.1038/nmat3238.
11. Threadgill, P., et al., *Friction stir welding of aluminium alloys.* International Materials Reviews, 2009.**54** : p. 49-93.DOI: 10.1179/174328009X411136.
12. Su, J.Q., et al., *Microstructural investigation of friction stir welded 7050-T651 aluminium.* Acta Materialia, 2003.**51** : p. 713-729.DOI: 10.1016/S1359-6454(02)00449-4.
13. Mahoney, M.W., et al., *Properties of friction-stir-welded 7075 T651 aluminium.* Metallurgical and Materials Transactions A, 1998.**29** (7): p. 1955-1964.DOI: 10.1007/s11661-998-0021-5.
14. Rhodes, C.G., et al., *Effects of friction stir welding on microstructure of 7075 aluminium.* Scripta Materialia, 1997.**36** : p. 69-75.
15. Jata, K. and S. Semiatin, *Continuous Dynamic Recrystallization During Friction Stir Welding of High Strength Aluminum Alloys.* Scripta Materialia - SCRIPTA MATER, 2000.**43** : p. 9.DOI: 10.1016/S1359-6462(00)00480-2.
16. Schmidt, H., J. Hattel, and J. Wert, *An analytical model for the heat generation in friction stir welding.* Modelling and Simulation in Materials Science and Engineering, 2003.**12** : p. 143.DOI: 10.1088/0965-0393/12/1/013.
17. Nagentrau, M., et al., *The influence of welding condition on the microstructure of WC hardfacing coating on carbon steel substrate.* International Journal of Refractory Metals & Hard Materials, 2019.**82** : p. 43-57.DOI: 10.1016/j.ijrmhm.2019.03.029.
18. de Sousa, J.M.S., et al., *Abrasion resistance of Fe-Cr-C coating deposited by FCAW welding process.* Wear, 2021.**476** : p. 12.DOI: 10.1016/j.wear.2021.203688.
19. Ferozhkhan, M.M., et al. *Plasma Transferred Arc Welding of Stellite 6 Alloy on Stainless Steel for Wear Resistance*. in *1st Global Colloquium on Recent Advancements and Effectual Researches in Engineering, Science and Technology (RAEREST)*. 2016. St Josephs Coll Engn & Technol, Palai, INDIA: Elsevier Science Bv.DOI: 10.1016/j.protcy.2016.08.226.
20. Appiah, A.N.S., et al., *Hardfacing of mild steel with wear-resistant Ni-based powders containing tungsten carbide particles using powder plasma transferred arc welding technology.* Materials Science-Poland, 2022.**40** (3): p. 42-63.DOI: 10.2478/msp-2022-0033.
21. Özel, C. and T. Gürgenç, *Effect of heat input on microstructure, wear and friction behaviour of (wt.-%) 50FeCrC-20FeW-30FeB coating on AISI 1020 produced by using PTA welding.* Plos One, 2018. **13**(1): p. 12.DOI: 10.1371/journal.pone.0190243.
22. Szymura, M., V. Ochodek, and L. Tanger. *COMPARISON OF ABRASIVE WEAR RESISTANCE OF ARC-SPRAYED AND HVOF-SPRAYED COATINGS AS WELL AS OVERLAY WELDS MADE USING*

SELF-SHIELDED FLUX-CORED WIRE. in *32nd International Conference on Metallurgy and Materials (METAL).* 2023. Brno, CZECH REPUBLIC: Tanger Ltd.DOI: 10.37904/metal.2023.4723.
23. Pawlowski, L., *The Science and Engineering of Thermal Spray Coatings*. 2008: Wiley.
24. Fotovvati, B., N. Namdari, and A. Dehghanghadikolaei, *On Coating Techniques for Surface Protection: A Review.* Journal of Manufacturing and Materials Processing, 2019.**3** (1): p. 28.
25. Lince, J., *Coatings for Aerospace Applications*. 2017.DOI: 10.13140/RG.2.2.21638.16964.
26. Holmberg, K. and A. Matthews, *Coatings Tribology: Properties, Mechanisms, Techniques and Applications in Surface Engineering*. 2009: Elsevier Science.
27. Berndt, C.C., et al., *Thermal Spray 2001: New Surfaces for a New Millenium; Proceedings of the 2nd International Thermal Spray Conference, 28-30 May, 2001, Singapore*. 2001: ASM International.
28. Philip A. Schweitzer, P.E., *Corrosion Resistance Tables: Metals, Nonmetals, Coatings, Mortars, Plastics, Elastomers, and Linings and Fabrics, Fifth Edition (4 Volume Set)*. 2004: Taylor & Francis.
29. Davis, J.R., *Alloying: Understanding the Basics*. 2001: ASM International.
30. Tayactac, R. and E. Ang, *A Review of Corrosion Resistance Alloy Weld Overlay Cladding Material for Geothermal Applications.* Materials Science Forum, 2021.**1047** : p. 120-127.DOI: 10.4028/www.scientific.net/MSF.1047.120.
31. Panwar, V., V. Chawla, and N. Grover, *A REVIEW ON DIFFERENT THERMAL SPRAY COATING PROCESS FOR INDUSTRIAL APPLICATIONS.* 2017.
32. Roy, M., *Surface Engineering for Enhanced Performance against Wear*. 2013. 1-319.DOI: 10.1007/978-3-7091-0101-8.
33. Fischer, T., *Materials Science for Engineering Students*. 2009: Academic Press.
34. Schütze, M., D.R. Holmes, and I.o. Corrosion, *Protective Oxide Scales and Their Breakdown*. 1997: Wiley.
35. Committee, M.S.M.M., et al., *Surface Modification Technologies: Proceedings of the ... International Conference on Surface Modification Technology*. 1994: Metallurgical Society.
36. Ren, X., L. Meng, and M. Soucek, *Environmentally Friendly Coatings*. 2016. p. 183-223.DOI: 10.1002/9781119185055.ch8.
37. Chavda, S.P., et al. *A Review on Optimisation of MIG Welding Parameters using Taguchi's DOE Method*. 2014.
38. Badheka, V.J., et al., *GTAW Application for Additive Manufacturing and Cladding of Steel Alloys*, in *Handbook of Smart Materials, Technologies, and Devices: Applications of Industry 4.0*, C.M. Hussain and P. Di Sia, Editors. 2022, Springer International Publishing: Cham. p. 1559-1579.DOI: 10.1007/978-3-030-84205-5_109.
39. Rashid, L., *Overlay welding of FeCrAl alloys*. 2016. p. 50.
40. Sun, G., et al., *Underwater Laser Welding/Cladding for High-performance Repair of Marine Metal Materials: A Review.* Chinese Journal of Mechanical Engineering, 2022.**35** (1): p. 5.DOI: 10.1186/s10033-021-00674-0.
41. Liu, Z., et al., *Electrodeposition of nanocrystalline Ni and NiCr alloy coatings: Effects of Cr content on microhardness and wear resistance improvement.* Journal of Materials Research and Technology, 2024.**30** : p. 3584-3593.DOI: https://doi.org/10.1016/j.jmrt.2024.04.100.
42. Singh, S., et al., *Applications and Developments of Thermal Spray Coatings for the Iron and Steel Industry.* Materials, 2023.**16** (2): p. 516.
43. Mishra, R.S. and Z.Y. Ma, *Friction stir welding and processing.* Materials Science and Engineering: R: Reports, 2005.**50** (1): p. 1-78.DOI: https://doi.org/10.1016/j.mser.2005.07.001.
44. Musalek, R., et al., *High-Temperature Cycling of Plasma Sprayed Multilayered NiCrAlY/YSZ/GZO/YAG Thermal Barrier Coatings Prepared from Liquid Feedstocks.* Journal of Thermal Spray Technology, 2021. **30**(1): pp. 81–96. DOI: 10.1007/s11666-020-01107-5.
45. Thakur, L. and H. Vasudev, *Thermal Spray Coatings*. 2021: CRC Press.
46. Gualco, A., H.G. Svoboda, and E.S. Surian, *Effect of welding parameters on microstructure of Fe-based Nanostructured Weld Overlay deposited through FCAW-S.* Soldagem & Inspecao, 2014. **19**(4): p. 314-322.DOI: 10.1590/0104-9224/si1904.04.
47. Wilden, J., J. Bergmann, and H. Frank, *Plasma Transferred Arc Welding—Modeling and Experimental Optimization.* Journal of Thermal Spray Technology, 2006.**15** : p. 779-784.DOI: 10.1361/105996306X146767.
48. Sousa, J., et al., *Tribological performance under abrasive wear of Fe-Cr-C plus Nb coating deposited by FCAW process.* Wear, 2023.**523** .DOI: 10.1016/j.wear.2023.204824.
49. Dizdar, S. and M. Kumar. *Fe-Based Powder Alloys Deposited by HVOF and HVAF for Applications Exposed to Solid Particle Erosion*. in *ITSC2015*. 2015.DOI: 10.31399/asm.cp.itsc2015p1013.
50. Czuprynski, A., *Comparison of Properties of Hardfaced Layers Made by a Metal-Core-Covered Tubular Electrode with a Special Chemical Composition.* Materials, 2020.**13** (23).DOI: 10.3390/ma13235445.
51. *ASTM G65-16(2021)*. Available from: https://www.astm.org/.

52. Malvajerdi, A.S., *Wear and coating of tillage tools: A review.* Heliyon, 2023.**9** (6): p. e16669.DOI: 10.1016/j.heliyon.2023.e16669.
53. Neogy, S., et al., *Piston and Rings for Diesel Engines*, in *Design and Development of Heavy Duty Diesel Engines: A Handbook*, P.A. Lakshminarayanan and A.K. Agarwal, Editors. 2020, Springer Singapore: Singapore. p. 731-761.DOI: 10.1007/978-981-15-0970-4_20.
54. Marosan A., G. Constantin, A.-L. Chicea, M. Crenganis, F. Morariu, *DESIGN OF MECHATRONIC MODULES THAT CAN FORM MULTIPLE CONFIGURATIONS OF MOBILE ROBOTS*. 2022.
55. Morariu F., T. Morariu, S.-G. Racz, *Mobile robot vision navigation strategy based on Pixy2 camera.* Materials Today: Proceedings, 2023.**93** : p. 636-640.DOI: https://doi.org/10.1016/j.matpr.2023.04.327.
56. Czupryński, A., *Comparison of Properties of Hardfaced Layers Made by a Metal-Core-Covered Tubular Electrode with a Special Chemical Composition.* Materials, 2020.**13** (23): p. 5445.
57. F. Morariu, R.D.R., , O. L. Petrașcu, A. Barsan, T. Morariu, A. Pascu, *Influence of 3D-Printing Strategies on the Compressibility of TPU 85A Elastomeric Material.* Acta Universitatis Cibiniensis. Technical Series, 2024.**76** : p. 28-33.DOI: 10.2478/aucts-2024-0004.
58. Shichalin, O.O., et al., *Functionally Gradient Material Fabrication Based on Cr, Ti, Fe, Ni, Co, Cu Metal Layers via Spark Plasma Sintering.* Coatings, 2023.**13** (1): p. 138.
59. Rusu D.-M., O.-L. Petrașcu, A. Barsan, T. Morariu, F. Morariu, A.-M. Pascu, *Analysis on the Impact of Industrial Agents on 3D-printed Polymeric Materials in Soft Robotics.* Materiale Plastice, 2025.**61** : p. 52-62.DOI: 10.37358/MP.24.4.5743.
60. Marosan A., G. Constantin, C.-E. Gîrjob, A.-L. Chicea, M. Crenganis, F. Morariu, *REAL-TIME DATA ACQUISITION WITH ESP32 FOR IOT APPLICATIONS USING OPEN-SOURCE MQTT BROKERS.* 2024. **19** : p. 61-68.
61. Naik, H.V. and V.D. Kalyankar, *Development of NiCrSiBC Weld Hardfacing Approach for P91 Steels Used in Steam Turbine Components.* Soldagem & Inspecao, 2021.**26** : p. 15.DOI: 10.1590/0104-9224/si26.08.
62. Lee, K.J. and D. Kim, *Effect of Tungsten Carbide Morphology, Quantity, and Microstructure on Wear of a Hardfacing Layer Manufactured by Plasma Transferred Arc Welding.* Metals, 2021.**11** (12): p. 14.DOI: 10.3390/met11122035.
63. Lozynskyi, V., et al., *Effect of Exothermic Additions in Core Filler on Arc Stability and Microstructure during Self-Shielded, Flux-Cored Arc Welding.* Crystals, 2024.**14** (4): p. 31.DOI: 10.3390/cryst14040335.
64. Perez, J., et al., *The Effect of Niobium Addition on the Operational and Metallurgical Behaviour of Fe-Cr-C Hardfacing Deposited by Shielded Metal Arc Welding.* Journal of Manufacturing and Materials Processing, 2024.**8** (1): p. 14.DOI: 10.3390/jmmp8010038.
65. Fagundes, J.G., et al., *Application of Titanium Machining Chips in Welding Consumables for Wear Resistant Hardfacing.* Soldagem & Inspecao, 2014.**19** (3): p. 264-270.DOI: 10.1590/0104-9224/si1903.09.
66. O'Brien, A., *Welding Handbook. Volume 2 - Part 1: Welding Processes*. Vol. 2. 2004, Miami, Florida: American Welding Society. 699.
67. Gramajo, J., A. Gualco, and H. Svoboda, *Effect of Welding Parameters on Nanostructured Fe-(C, B)-(Cr, Nb) Alloys.* Materials Research-Ibero-American Journal of Materials, 2019.**22** (6): p. 8.DOI: 10.1590/1980-5373-mr-2019-0469.
68. Simson, T., et al., *Comparison of Plasma Transferred Arc and Submerged Arc Welded Abrasive Wear Resistant Composite Hardfacings.* Materials Science-Medziagotyra, 2018.**24** (2): p. 172-176.DOI: 10.5755/j01.ms.24.2.19121.
69. Oo, H.Z., B. Srikarun, and P. Muangjunburee, *Correlating Hardness and Welding Dilution with the Abrasion Mass Loss of Hardfacings Welded with Different Currents and Polarities.* Metallurgist, 2018.**61** (11-12): p. 1033-1037.DOI: 10.1007/s11015-018-0604-3.
70. Saha, A. and S.C. Mondal, *Multi-objective Optimization of Welding Parameters in MMAW for Nano-structured Hardfacing Material Using GRA Coupled with PCA.* Transactions of the Indian Institute of Metals, 2017.**70** (6): p. 1491-1502.DOI: 10.1007/s12666-016-0945-1.
71. Saha, A. and S.C. Mondal, *Multi-criteria selection of optimal welding parameter in MMAW hardfacing using MOORA method coupled with PCA.* International Journal of Materials & Product Technology, 2018.**57** (1-3): p. 240-255.DOI: 10.1504/ijmpt.2018.092940.
72. Abed, H., F.M. Ghaini, and H.R. Shahverdi, *Characterisation of Fe49Cr18Mo7B16C4N b6 high-entropy hardfacing layers produced by gas tungsten arc welding (GTAW) process.* Surface & Coatings Technology, 2018.**352** : pp. 360-369.DOI: 10.1016/j.surfcoat.2018.08.019.
73. Bhaduri, A.K., *Development and Deployment of Welding Technologies for the Indian Sodium-Cooled Fast Reactor and Advanced Ultra-supercritical Thermal Power Programmes.* Transactions of the Indian Institute of Metals, 2021.**74** (5): p. 1035-1053.DOI: 10.1007/s12666-021-02260-3.

74. Brownlie, F., et al., *Comparison of Hot Wire TIG Stellite 6 weld cladding and lost wax cast Stellite 6 under corrosive wear conditions.* Wear, 2018.**404** : p. 71-81.DOI: 10.1016/j.wear.2018.03.004.
75. Oo, H.Z., B. Srikarun, and P. Muangjunburee, *The effects of heat input and polarity on wear resistance of Fe-3.5% Cr steel hardfaced using submerged arc welding.* Materials Research Express, 2019.**6** (10): p. 11.DOI: 10.1088/2053-1591/ab34c7.
76. Rauta, R.P., et al., *Influence of Pushing and Pulling the Electrode Procedure and Addition of Second Layer of Welding on the Wear in Hardfacing of Fe-Cr-C.* Materials Research-Ibero-American Journal of Materials, 2016. **19**(5): p. 1193-1200.DOI: 10.1590/1980-5373-mr-2016-0230.
77. Saha, A. and S.C. Mondal, *Statistical Analysis and Optimisation of Process Parameters in Wire Cut Machining of Welded Nanostructured Hardfacing Material.* Silicon, 2019.**11** (3): p. 1313-1326.DOI: 10.1007/s12633-018-9924-y.
78. Rajkumar, V., T.V. Arjunan, and A.R. Kannan, *Investigations on hardfacing and wear characteristics of nickel-based Inconel 625 overlaid welds over AISI 347 pipe.* Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2020. **42**(1): p. 12.DOI: 10.1007/s40430-019-2092-1.
79. Sutka, J. and R. Konar, *The Effect of Mixing the Additive Material with the Substrate during the Renovation of the Foundry Mold by TIG Welding Hardfacing.* Manufacturing Technology, 2023.**23** (3): p. 341-347.DOI: 10.21062/mft.2023.033.
80. Gucwa, M., et al., *The Effect of Type of Welding Sequence During Hardfacing Chromium Cast Iron for Erosion Resistance.* Archives of Foundry Engineering, 2017.**17** (3): p. 51-54.DOI: 10.1515/afe-2017-0089.
81. Moreno-Uribe, A.M., et al., *Flux Filling Rate Effect on Weld Bead Deposition of Recycled Titanium Chip Tubular Wire.* International Journal of Precision Engineering and Manufacturing-Green Technology, 2024: p. 9.DOI: 10.1007/s40684-024-00658-0.
82. Rajeev, G.P., M. Kamaraj, and S.R. Bakshi, *Hardfacing of AISI H13 tool steel with Stellite 21 alloy using cold metal transfer welding process.* Surface & Coatings Technology, 2017.**326** : p. 63-71.DOI: 10.1016/j.surfcoat2017.07.050.
83. Günther, K. and J.P. Bergmann, *Influencing Microstructure of Vanadium Carbide Reinforced FeCrVC Hardfacing during Gas Metal Arc Welding.* Metals, 2020.**10** (10): p. 14.DOI: 10.3390/met10101345.
84. Tavodova, M., L. Falat, and V. Skultetyova, *LABORATORY ANALYSIS OF HARDFACING MATERIAL APPLIED BY PLASMA AND TIG WELDING.* Mm Science Journal, 2020.**2020** : p. 3826-3831.DOI: 10.17973/mmsj.2020_03_2019131.
85. Leitner, M., et al., *Wear and fatigue resistance of mild steel components reinforced by arc welded hard layers.* Surface & Coatings Technology, 2017.**330** : p. 140-148.DOI: 10.1016/j.surfcoat.2017.09.046.
86. Wilhelm, G., G. Gött, and D. Uhrlandt, *Study of flux-cored arc welding processes for mild steel hardfacing by applying high-speed imaging and a semi-empirical approach.* Welding in the World, 2017. **61**(5): p. 901-913.DOI: 10.1007/s40194-017-0485-2.
87. Pawlik, J., et al., *On the Influence of Linear Energy/Heat Input Coefficient on Hardness and Weld Bead Geometry in Chromium-Rich Stringer GMAW Coatings.* Materials, 2022.**15** (17): p. 20.DOI: 10.3390/ma15176019.
88. Kaptanoglu, M. and M. Eroglu, *INVESTIGATION OF HARDFACING DEPOSITS OBTAINED BY USING SUBMERGED ARC WELDING FLUXES CONTAINING HIGH-CARBON FERROCHROMIUM AND FERROBORON.* Archives of Metallurgy and Materials, 2023. **68**(3): p. 895-905.DOI: 10.24425/amm.2023.145453.
89. Nguyen, M.T., et al., *An experimental study on the quality of hardfacing layer through resistance seam welding.* Journal of Advanced Joining Processes, 2024.**9** : p. 13.DOI: 10.1016/j.jajp.2024.100230.
90. Mitelea, I., et al., *Cavitation Erosion of the Austenitic Manganese Layers Deposited by Pulsed Current Electric Arc Welding on Duplex Stainless Steel Substrates.* Crystals, 2024.**14** (4): p. 17.DOI: 10.3390/cryst14040315.
91. Zahiri, R., et al., *Hardfacing using ferro-alloy powder mixtures by submerged arc welding.* Surface & Coatings Technology, 2014.**260** : p. 220-229.DOI: 10.1016/j.surfcoat.2014.08.076.
92. Günther, K., J.P. Bergmann, and D. Suchodoll, *Hot wire-assisted gas metal arc welding of hypereutectic FeCrC hardfacing alloys: Microstructure and wear properties.* Surface & Coatings Technology, 2018.**334** : p. 420-428.DOI: 10.1016/j.surfcoat.2017.11.059.
93. Bendikiene, R., et al., *Study of submerged and plasma arc welded composite hardfacings with a novel Cr₃C₂-Ni reinforcement.* Proceedings of the Estonian Academy of Sciences, 2019.**68** (2): p. 150-157.DOI: 10.3176/proc.2019.2.06.
94. Pournajaf, E., A. Abbasi, and H. Najafi, *Microstructure and Wear Resistance of Single- and Multi-Layered Low-Carbon Fe-Cr-C-Mo-Mn Clads Deposited by Shielded Metal Arc Welding.* Journal of Materials Engineering and Performance, 2021. **30**(10): pp. 7704-7715.DOI: 10.1007/s11665-021-05901-2.

95. Oo, H.Z. and P. Muangjunburee. *Wear behaviour of hardfacing on 3.5% chromium cast steel by submerged arc welding*. in *10th Thailand International Metallurgy Conference (TIMETC) - Innovation through Industrial Creation*. 2017. Bangkok, THAILAND: Elsevier Science Bv.DOI: 10.1016/j.matpr.2017.10.101.
96. Mendez, P.F., et al., *Welding processes for wear resistant overlays.* Journal of Manufacturing Processes, 2014.**16** (1): p. 4-25.DOI: 10.1016/j.jmapro.2013.06.011.
97. Oo, H.Z. and P. Muangjunburee, *Hardfacing of thermite welded rail by flux-cored arc welding.* Wear, 2024.**546** : p. 14.DOI: 10.1016/j.wear.2024.205314.
98. Trembach, B., et al., *Influence of the core filler composition on the recovery of alloying elements during the self-shielded flux-cored arc welding.* Journal of Materials Research and Technology-Jmr&T, 2020. **9**(5): p. 10520-10528.DOI: 10.1016/j.jmrt.2020.07.052.
99. Brezinová, J., et al., *Influence of the Hardfacing Welds Structure on Their Wear Resistance.* Metals, 2016.**6** (2): p. 12.DOI: 10.3390/met6020036.
100. Zhang, X.Z., et al., *Microstructure and Hardness Investigation of Tribaloy Alloy T-400C Hardfacing Deposited on Nickel-Based Alloy Inconel 740H via Plasma Transferred Arc Welding Subjected to Long-Time Aging.* Metallography Microstructure and Analysis, 2024.**13** (1): p. 145-173.DOI: 10.1007/s13632-024-01040-x.
101. Lima, A.C., V.A. Ferraresi, and R.P. Reis, *Performance Analysis of Weld Hardfacings Used in the Sugar/Alcohol Industry.* Journal of Materials Engineering and Performance, 2014.**23** (5): p. 1823-1833.DOI: 10.1007/s11665-014-0948-1.
102. Dumovic, M. and D. Dunne, *Prediction of weld metal microstructure of self-shielded arc hardfacing welds resistant to metal-to-metal wear.* Welding in the World, 2014.**58** (6): p. 831-837.DOI: 10.1007/s40194-014-0162-7.
103. Colaço, F.H.G. and O. Maranho, *Evaluation of Mass Loss of Weld-Deposited Hardfacing with Cored Wire Ti-FeCrC Alloy.* Soldagem & Inspecao, 2014. **19**(1): p. 58-68.DOI: 10.1590/s0104-92242014000100008.
104. Srikarun, B., H.Z. Oo, and P. Muangjunburee, *Influence of Different Welding Processes on Microstructure, Hardness, and Wear Behaviour of Martensitic Hardfaced Cladding.* Journal of Materials Engineering and Performance, 2021. **30**(12): p. 8984-8995.DOI: 10.1007/s11665-021-06109-0.
105. Sadhu, A., et al., *Performance Evaluation of Laser-Deposited Functionally Graded Stellite 6-WC Tools in Friction Stir Lap Welding of CuCrZr-SS304.* Journal of Materials Engineering and Performance, 2024: p. 20.DOI: 10.1007/s11665-024-09980-9.
106. Gramajo, J., A. Gualco, and H. Svoboda, *Study of the welding procedure in nanostructured super-hard Fe- (Cr, Mo, W) - (C, B) hardfacing.* International Journal of Refractory Metals & Hard Materials, 2020.**88** : p. 6.DOI: 10.1016/j.ijrmhm.2020.105178.
107. ****Welding Alloys*. Available from: https://www.welding-alloys.com/product/h-frame-welding-machine/#tab-id-2.
108. ****Technical specifications manual*. Available from: https://www.welding-alloys.com/wp-content/uploads/2021/12/H-Frame.pdf.
109. *** *Welding Alloys user manual*.
110. *** *Welding Alloys manufacturer brochure*. Available from: https://www.welding-alloys.com/wp-content/uploads/2022/11/1713_H-Frame-Machine-flyer.pdf.
111. *** *Miller Dimension 650 manual*. Available from: https://www.millerwelds.com/-/media/inriver/dc193-dimension-650--english.pdf.
112. *** *Miller Dimension Series Manual*. Available from: https://www.millerwelds.com/-/media/miller-electric/files/pdf/products/international-spec-sheets/multiprocess/dc19-2.pdf.
113. *** *Corodur 56 brochure*. Available from: https://www.corodur.de/datenblaetter/56_gb.pdf.
114. *** *CORODUR® 56 OA Ø 2.4 mm Certificate of Conformity*.
115. Tandon, D., et al., *A Review on Hardfacing, Process Variables, Challenges, and Future Works.* Metals, 2023.**13** (9): p. 1512.
116. M.S., G., *Welding course notes*. 2018: Iași.
117. O'Brien, A. and C. Guzman, *Welding Handbook. Volume 3 - Part 2: Welding Processes*. 2007: American Welding Society AWS.
118. Siva Prasad, K., C.S. Rao, and N. Damera, *Application of Taguchi based Design of Experiments to Fusion Arc Weld Processes: A Review.* International Journal of Business Research and Development, 2013.**2** : p. 1-8.DOI: 10.24102/ijbrd.v4i3.575.
119. Zoalfakar, S. and A. Hassan, *Analysis and Optimisation of Shielded Metal Arc Welding Parameters on Mechanical Properties of Carbon Steel Joints by Taguchi Method.* 2017.
120. Satheesh, M. and J.E.R. Dhas, *MULTI OBJECTIVE OPTIMIZATION OF FLUX CORED ARC WELD PARAMETERS USING FUZZY BASED DESIRABILITY FUNCTION.* Iranian Journal of Science and Technology-Transactions of Mechanical Engineering, 2013.**37** (M2): p. 175-187.

121. Elrabei, T. and E. Anawa, *MULTI OBJECTIVE OPTIMIZATION OF TIG WELDING PROCESS PARAMETERS USING FUZZY BASED TAGUCHI METHODOLOGY.* Journal of Engineering Research, 2018. **September 2018**: p. 37.
122. Satheesh, M. and J. Dhas, *Multi Objective Optimization of Weld Parameters of Boiler Steel Using Fuzzy Based Desirability Function.* Journal of Engineering Science and Technology Review, 2014.**7** : p. 29-36.DOI: 10.25103/jestr.071.05.
123. Saini, V. and S. Singla, *Parameter Optimization of SAW in Hardfacing Process Using Hybrid Approach of Adaptive Stimulated Annealing and Neural Networks.* Asian Journal of Engineering and Applied Technology, 2012. **1- No 2**.DOI: 10.51983/ajeat-2012.1.2.2495.
124. Singla, Y., et al., *Enhancing the wear resistance of iron-based alloys: A comprehensive review of alloying element effects.* Journal of Manufacturing Processes, 2024.**120** : p. 135-160.DOI: 10.1016/j.jmapro.2024.04.038.
125. Scheffé, H., *The Analysis of Variance*. 1999: Wiley.
126. Kutner, M.H., *Applied Linear Statistical Models*. 2005: McGraw-Hill Irwin.
127. Montgomery, D.C., *Design and Analysis of Experiments*. 2017: John Wiley & Sons, Incorporated.
128. Montgomery, D.C., E.A. Peck, and G.G. Vining, *Introduction to Linear Regression Analysis*. 2012: Wiley.
129. Tahaei, A., et al., *The hardfacing properties of the nickel-based coating deposited by the PTA process with the addition of wc nano-particles: Wear investigation.* Tribology International, 2024.**193** : p. 109472.DOI: https://doi.org/10.1016/j.triboint.2024.109472.
130. Suthar, F.V., et al., *Optimisation of GTAW process parameters for deposition of nickel-based hardfacing alloy using Taguchi method.* Welding in the World, 2023.**67** (8): p. 1951-1966.DOI: 10.1007/s40194-023-01540-4.
131. Zhang, S.D., et al., *Characterisation of three-dimensional porosity in an Fe-based amorphous coating and its correlation with corrosion behaviour.* Corrosion Science, 2015.**93** : p. 211-221.DOI: https://doi.org/10.1016/j.corsci.2015.01.022.
132. Zhang, S.D., et al., *Effect of porosity defects on the long-term corrosion behaviour of Fe-based amorphous alloy coated mild steel.* Corrosion Science, 2016.**110** : p. 57-70.DOI: https://doi.org/10.1016/j.corsci.2016.04.021.
133. Liu, D., et al., *Development of Nickel-Added, Iron-Based, Slag-Free, Self-Shielded Metal-Cored Wire <i>The effects of nickel on the microstructure and wear performance of hardfacing alloys are investigated</i>.* Welding Journal, 2018. **97**(9): p. 263S-272S.DOI: 10.29391/2018.97.023.
134. Ni, Y., et al., *Corrosion mechanism of CuAl-NiC abradable seal coating system—The influence of porosity, multiphase, and multilayer structure on the corrosion failure.* Journal of Materials Science & Technology, 2021.**88** .DOI: 10.1016/j.jmst.2021.01.068.
135. Singla, Y.K., D.K. Dwivedi, and N. Arora, *On the modelling of dry sliding adhesive wear parameters of vanadium additive iron-based alloys at elevated temperatures.* Surface & Coatings Technology, 2015.**283** : p. 223-233.DOI: 10.1016/j.surfcoat.2015.10.078.
136. Tougherghi, F., et al., *Microstructure, Tribological, and Electrochemical Characterisation of Hardfacing WC-Ni-Cr on AISI 1045 Carbon Steel Alloy.* Journal of Materials Engineering and Performance, 2022. **31**(9): pp. 7641–7652. DOI: 10.1007/s11665-022-06781-w.
137. Han, S.-W., et al., *GMA process development for pore-free zinc-coated steel sheet welding in automotive industry.* The International Journal of Advanced Manufacturing Technology, 2023.**126** (9): p. 3849-3859.DOI: 10.1007/s00170-023-11338-9.
138. Huang, Y., et al., *EMD-based pulsed TIG welding process porosity defect detection and defect diagnosis using GA-SVM.* Journal of Materials Processing Technology, 2016.**239** .DOI: 10.1016/j.jmatprotec.2016.07.015.
139. García-Moreno, A.I., et al., *Image-based porosity classification in Al-alloys by laser metal deposition using random forests.* The International Journal of Advanced Manufacturing Technology, 2020.**110** : p. 1-19.DOI: 10.1007/s00170-020-05887-6.
140. Ahsan, R., et al., *Porosity formation mechanisms in cold metal transfer (CMT) gas metal arc welding (GMAW) of zinc coated steels.* Science and Technology of Welding & Joining, 2016.**21** : p. 209-215.DOI: 10.1179/1362171815Y.0000000084.
141. Gualco, A., H.G. Svoboda, and E.S. Surian, *Effect of Heat Input on the Fe-based Nanostructured Weld Overlay.* Soldagem & Inspecao, 2013. **18**(4): pp. 329–338. DOI: 10.1590/s0104-92242013000400005.
142. Jenney, C.L. and A. O'Brien, *Welding Handbook. Volume 1, Welding Science and Technology*. 2001: American Welding Society AWS.
143. Trembach, B., et al., *Application of Taguchi method and ANOVA analysis for optimisation of process parameters and exothermic addition (CuO-Al) introduction in the core filler during self-shielded flux-*

cored arc welding. International Journal of Advanced Manufacturing Technology, 2021.**114** (3-4): p. 1099-1118.DOI: 10.1007/s00170-021-06869-y.
144. Gualco, A., et al., *Influence of Heat Input on Microstructure in Multicomponents (Cr, Mo, W, Nb, C, B) Fe-Based Nanostructured Hardfacings.* Soldagem & Inspecao, 2017. **22**(3): pp. 240–248. DOI: 10.1590/0104-9224/si2203.02.
145. Bembenek, M., et al., *Microstructure and Wear Characterisation of the Fe-Mo-B-C-Based Hardfacing Alloys Deposited by Flux-Cored Arc Welding.* Materials, 2022.**15** (14).DOI: 10.3390/ma15145074.
146. Guzman, C. and A. O'Brien, *Welding Handbook. Volume 4 - Part 1: Materials and Applications*. 2010: American Welding Society AWS.
147. Cunha, M.C., et al., *Microstructural and wear investigation of FeCrC and FeCrC-NbB hardfacing alloys deposited with FCAW-S.* International Journal of Advanced Manufacturing Technology, 2025. **136**(3-4): p. 1241-1251.DOI: 10.1007/s00170-024-14936-3.
148. Gucwa, M., et al., *Structure and Properties of Coatings Made with Self Shielded Cored Wire.* Archives of Foundry Engineering, 2016.**16** (3): p. 39-42.DOI: 10.1515/afe-2016-0046.
149. *Olympus DELTA Element brochure*. Available from: https://www.aaatesters.com/pub/media/datasheets/olympus_de-2000_delta_element_specifications_spec_sheet.pdf?srsltid=AfmBOoqsf9-2LBoEUWqbppYlLlpFaZJZ7k4diOCjUZzCKPWyWfZRlWTm.
150. Torres, H., M. Varga, and M.R. Ripoll, *High temperature hardness of steels and iron-based alloys.* Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing, 2016.**671** : p. 170-181.DOI: 10.1016/j.msea.2016.06.058.
151. Paek, D.S. and C. Bin Jong, *Investigation of carbide precipitations on microstructure and hardness of medium carbon Cr-Ni austenite stainless hardfacing deposit with high wear resistance properties.* Welding in the World, 2022. **66**(6): pp. 1111–1119. DOI: 10.1007/s40194-021-01231-y.
152. Rajkumar, V., et al. *Effect of Heat Input on Micro-Hardness and Shear Strength of Inconel 625 Hardfacing onto AISI 347 Steel pipes by GMAW Process*. in *2nd Biennial International Conference on Aerospace and Mechanical Engineering (ICAME).* 2018. Kollam, INDIA.DOI: 10.1088/1742-6596/1355/1/012029.
153. Balaguru, S., et al., *Effect of dilution on micro hardness of Ni-Cr-B-Si alloy hardfaced on austenitic stainless steel plate for sodium-cooled fast reactor applications.* Nuclear Engineering and Technology, 2020.**52** (3): p. 589-596.DOI: 10.1016/j.net.2019.08.011.
154. Spornic, L.C., *Contributions to the optimisation of thermomechanical treatments in the electric pressure welding cycle* UNIVERSTATEA „POLITEHNICA " TIMIŞOARA
155. Lippold, J.C. and D.J. Kotecki, *Welding Metallurgy and Weldability of Stainless Steels*. 2005: Wiley.
156. Basyirun, B., et al., *Hardness and Microstructure Characterisation of Hardfacing Alloys Deposited by Shielded Metal Arc Welding (SMAW) on AISI 1045 Medium Carbon Steel.* International Journal of Integrated Engineering, 2024.**16** (5): p. 88-99.DOI: 10.30880/ijie.2024.16.05.008.
157. Pawlik, J., et al., *On the Influence of Linear Energy/Heat Input Coefficient on Hardness and Weld Bead Geometry in Chromium-Rich Stringer GMAW Coatings.* Materials, 2022.**15** (17).DOI: 10.3390/ma15176019.
158. Singh, S., et al. *Analysis of wear and hardness during surface hardfacing of alloy steel by thermal spraying, electric arc and TIG welding*. in *2nd International Conference on Functional Material, Manufacturing and Performances (ICFMMP)*. 2021. Phagwara, INDIA.DOI: 10.1016/j.matpr.2021.09.122.
159. Staff, A.I. and A.I.H. Committee, *ASM Handbook: Heat Treating. Vol. 4*. 1990: A S M International.
160. Meszaros, K., et al., *Abrasion resistance and hardness evaluation of FCAW-S hard-facing following elevated temperature exposure.* Wear, 2023.**523** .DOI: 10.1016/j.wear.2023.204759.
161. *** *INSIZE ISH-BRV brochure* Available from: https://m.insize.com/page-26-1203-1nl8u5.html.
162. de Sousa, J.M.S., et al., *Abrasion resistance of Fe-Cr-C coating deposited by FCAW welding process.* Wear, 2021.**476** .DOI: 10.1016/j.wear.2021.203688.
163. TUDOR, A.M., *Course notes - Integrated Tribosystems*.
164. Coronado, J.J., H.F. Caicedo, and A.L. Gómez, *The effects of welding processes on abrasive wear resistance for hardfacing deposits.* Tribology International, 2009.**42** (5): p. 745-749.DOI: 10.1016/j.triboint.2008.10.012.
165. cruz-crespo, A., et al., *Microstructure and Abrasion Resistance of Fe-Cr-C and Fe-Cr-C-Nb Hardfacing Alloys Deposited by S-FCAW and Cold Solid Wires.* Soldagem & Inspeção, 2016.**21** : p. 342-353.DOI: 10.1590/0104-9224/SI2103.09.
166. Blau, P.J., *ASM Handbook, Volume 18 - Friction, Lubrication, and Wear Technology*. ASM International.
167. Najarro-Quintero, R., et al., *Effect of the Matrix, Graphite and Ferrochrome-Manganese Contents in SAW Fluxes, Obtained with Steel Slag and Rice Husk Ash, on the Chemical Composition and Hardness of the Metal Deposited in One Layer.* Soldagem & Inspecao, 2022.**27** .DOI: 10.1590/0104-9224/si27.11.

168. *** *MECAPRESS 3 brochure*. Available from: https://www.presi.com/en/product/mecapress-3/.
169. *** *ATA Saphir 530 Brochure*. Available from: https://www.neurtek.com/descargas/atm_saphir_530_rubin_500_en.pdf.
170. *** *Leica DM1750 M microscope*. Available from: https://www.leica-microsystems.com/products/light-microscopes/p/leica-dm1750-m/downloads/.
171. Ban, M., et al., *Wear Resistance Property of Hardfacing Weld Overlays Containing Metal Carbides.* Tribology Online, 2012.**7** : p. 207.DOI: 10.2474/trol.7.207.
172. Gontcharov, A., et al., *Advanced Welding Materials and Technologies for Repair of Turbine Engine Components Manufactured of High Gamma Prime Nickel Based Superalloys*. 2018. V006T24A013.DOI: 10.1115/GT2018-75862.
173. Balakrishnan, M., V. Balasubramanian, and G.M. Reddy, *Effect of PTA Hardfaced Interlayer Thickness on Ballistic Performance of Shielded Metal Arc Welded Armour Steel Welds.* Journal of Materials Engineering and Performance, 2013. **22**(3): pp. 806-814.DOI: 10.1007/s11665-012-0338-5.
174. Cortés-Rodríguez, R., et al., *Mechanical properties of AISI 1045 carbon steel plates weld overlay with EnDOTec DO15 using CMT and GMAW-P.* International Journal of Advanced Manufacturing Technology, 2024.**132** (7-8): p. 3535-3551.DOI: 10.1007/s00170-024-13523-w.
175. Bakhshayesh, M.M., et al., *Evaluation of crane wheels restored by hardfacing two distinct 13Cr-4Ni martensitic stainless steels.* Journal of Materials Research and Technology-Jmr&T, 2023.**26** : p. 6067-6083.DOI: 10.1016/j.jmrt.2023.08.292.
176. Kumar, N.P., N.S. Shanmugam, and G. Sreedhar, *High cycle fatigue behaviour of Inconel 625 weld overlay on AISI 316L plate.* Surface & Coatings Technology, 2021.**415** : p. 11.DOI: 10.1016/j.surfcoat.2021.127138.
177. Akpinar, D.E., S. Dilibal, and U. Gürol, *EXPERIMENTAL INVESTIGATION ON WAAM-BASED FUNCTIONAL HARD-FACING BIMETALLIC PART.* Journal of Mining and Metallurgy Section B-Metallurgy, 2024. **60**(2): p. 283-293.DOI: 10.2298/jmmb240505020a.
178. Beaurin, G., et al., *Microstructural and mechanical properties evolutions of plasma transferred arc deposited Norem02 hardfacing alloy at high temperature.* Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing, 2011.**528** (15): p. 5096-5105.DOI: 10.1016/j.msea.2011.02.077.
179. Kumar, N.P. and N.S. Shanmugam, *Some studies on nickel-based Inconel 625 hard overlays on AISI 316L plate by gas metal arc welding-based hardfacing process.* Wear, 2020.**456** .DOI: 10.1016/j.wear.2020.203394.
180. F. Morariu, T. Morariu, A. Bârsan, S.-G. Racz. *The Influence of Welding Row Orientation on Mechanical Properties for Hardfacing Wear Plates* in *40th Danubia-Adria Symposium on Advances in Experimental Mechanics,*. 2024. Institute of Fundamental Technological Research of the Polish Academy of Sciences (IPPT PAN).
181. Liu, S., et al., *Effect of Nb additive on wear resistance and tensile properties of the hypereutectic Fe-Cr-C hardfacing alloy.* Materials Today Communications, 2020.**24** .DOI: 10.1016/j.mtcomm.2020.101232.
182. Morariu F., T. Morariu, A. Bârsan, S.-G. Racz, A.-I. Maroșan, H.-A. Brănescu, *The Determination of Mechanical Properties by Tensile Testing of Hardfacing Wear Plates*, ACTA TECHNICA NAPOCENSIS, 2025. 68 (2) Issue II Special: p. 222-229 – Accepted for publication.
183. *** *GOM ARAMIS 2M Manual*. Available from: https://www.manualslib.com/manual/2969735/Gom-Aramis.html.
184. *** *Zeiss Aramis*. Available from: https://www.zeiss.com/metrology/en/systems/optical-3d/3d-testing/aramis-adjustable.html.
185 Morariu, F., T. Morariu, A. Bârsan, S.-G. Racz, D. Dobrotă, *Evaluation of Hardfacing Layers Applied by FCAW-S on S355MC Steel and Their Influence on Its Mechanical Properties*. Materials 2025 – Accepted for publication.