RIGA TECHNICAL UNIVERSITY

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THE EFFECT OF SHIELDING GAS ON THE WELDING PROCESS AND WELD SEAM IN SEMI-AUTOMATIC WELDING OF HIGH STRENGTH STEEL

Summary of the Doctoral Thesis

RTU Press
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Faculty of Mechanical Engineering, Transport and Aeronautics
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DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotation Council on 14 December 2022 at the Faculty of Mechanical Engineering, Transport and Aeronautics of Riga Technical University, 6 b Ķīpsalas Street, Room 204.

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Didzis Avišāns ……………………………. (signature)

Date: ……………………

The Doctoral Thesis has been written in English. It consistsof an Introduction, 3 chapters, Conclusions, 48 figures, 9 tables, 6 appendices; total number of pages is 71, excluding appendices. The bibliography contains 66 titles.

CONTENTS

GENERAL CHARACTERISTICS OF THE THESIS

Actuality of the topic

Welding of high-strength steels is becoming more important in modern production. These materials allow to reduce the weight of structures with a minimal increase in cost. Semi-automatic gas shielded welding (Metal Active Gas (MAG)) is widely used in the production of steel constructions. One of the main tasks during this process is not to lose the mechanical properties of the material. Metallurgical processes take place in the weld during welding – melting of the metal, change of the composition of chemical and alloying elements, re-formation of the metal micro structure as the metal cools down. These processes are significantly influenced by the used consumables, shielding gas and chosen welding parameters.

Many investigations till nowadays have focused on the short-arc welding of low-alloy steels (235–355 MPa) with wire transfer in the form of droplets. As a result, slower seam formation occurs and the thermal effect or heat input to the weld is higher. On the other hand, changes in alloying materials as well as the mechanical properties of the material are not significantly affected. These studies also highlight the influence of shielding gas on welding process. Many studies suggest a mixture of 25 % CO_2 (Carbon Dioxide) with Ar (argon) as one of the best mixtures [5], [14], [29], [31]. Similar studies have been performed on the welding of very high strength steels (890–1000 MPa) [38], [40], [42], [43]. These studies emphasize that shielding gas mixtures with a lower CO_2 content with Ar give better results. Some of these studies have been performed by welding with welding parameters that ensure the spray-arc transition of the melting electrode. This allows to increase the welding speed and reduce heat input. As a result, the formation of the welding seam and metallurgical processes take place faster, the arc temperature rises, the molten material becomes more liquid, and the seam formation process is not so easy to control [14]. However, the increased presence of CO_2 in the shielding gas and during welding increases the possibility of short-circuiting, which can result in the burning of significant alloying materials. This can lead to a deterioration of the mechanical properties of the weld, which can become the weakest point in the structure.

Analyzing the research carried out in recent years, it was concluded that there is a lack of research on welding of low-alloy high-strength steels (420–850 MPa). These materials are increasingly used and in demand not only in Latvia but also in other markets. Therefore, it can be concluded that the study on the welding of low-alloyed high-strength steels and the effect of shielding gas on the process is actual. In recent years, welding equipment manufacturers have been offering high-capacity and high-performance equipment, enabling companies to increase production capacity by increasing welding parameters. Therefore, the study of high welding parameters and welding in the spray-arc transfer mode and their effect on the mechanical properties of the welding joint is also very important.

Hypothesis

In MAG with spray-arc transfer welding of low-alloy high-strength steels (420–850 MPa), the hardness of the welded joint material decreases due to the increase of

CO_2 content as well as the addition of O_2. Based on this assumption, a study was conducted, which is presented in the Thesis.

The aim and objectives of the Thesis

The aim of the Doctoral Thesis is to investigate and define the effect of MAG welding with spray-arc parameters and shielding gas mixture on the mechanical properties, microstructural changes and chemical composition of welded compounds in low-alloy high-strength steels. As a result of the research, it is planned to develop a mathematical model that would help to predict the mechanical properties and alloying materials like Mn of the welded joint depending on the welding parameters and the use of shielding gas.

Several tasks were performed to achieve the goal:

1. Research of previous investigations and their analysis.
2. Welding of samples with different shielding gases, with different welding parameters, which ensures the transfer of the melting electrode in spray-arc.
3. Visual testing of welded specimens.
4. Analysis of the chemical composition of the weld metal.
5. Examination of the mechanical (hardness) properties of the obtained compound.
6. Analysis of the newly created microstructure.
7. Approbation of the obtained research results.

Research methods

Qualitative and quantitative research methods were used to achieve the set goals and solve the tasks, as well as the technical support of the experiments is listed and described.

In order to ensure the high-quality results of the performed experiments, one of the best welding equipment *FRONIUS® (Switzerland)* was chosen for the tests. One of the most recently developed equipment, *Fronius®500i*, was used for the experiments, which ensures the fulfillment of the intended high current parameters, as well as stable transfer of the welding electrode, which is an essential condition for this study. It was mechanized with a *FRONIUS®FlexTrack 45 Pro (Switzerland)* welding tractor to ensure a stable welding process. For precise selection of welding parameters, the application *WeldConnect®* developed by *FRONIUS®* was used, with the help of which the appropriate welding parameters were selected, which would ensure the transfer of the melting electrode in a spray-arc, keeping the setted welding seam size.

Samples were prepared in such a way that it was possible to perform further research of the microstructure of the welded joint, penetration and melting, chemical analysis and hardness measurements after the performed experiments. Laboratory equipment *Texmet 2000 (Italy)* was used for sample preparation. The prepared samples were then etched with 9 % nitric acid. It was then possible to see the shape of the weld, and further studies and measurements of the welding joint were possible to be performed. The size and amounts of pores and other inclusions were determined using an *Axiovert 40 MAT optical microscope (Germany)* at 50x magnification. The location of the grains of the formed micro-structure and their formation was determined with a magnification of 200 times. Using the optical spectrometer *HITACHI PMI-MASTER Pro2 (Japan)*, the chemical composition of both the base material and the newly formed weld was determined, after which further work conclusions were made. The hardness of the obtained samples was measured with a *Mitutoyo Micro Vickers hardness tester HM-210D (Japan).*

Statistical methods used in data processing: descriptive/descriptive statistics, inferential statistical method used to determine correlations – multifactor regression analysis and correlation analysis. The results are displayed in the form of graphs, images and tables.

Scientific novelty

- It has been proven that welding shielding gas with a reduced percentage of carbon dioxide in argon provides the properties of the welded material and the proportions of the chemical composition more in line with the base material when welding with melting electrodes at high welding parameters.
- A new model has been developed, with the help of which it is possible to predict the influence of the selected welding parameters and the percentage of shielding gas on the properties of the welded joint.
- It has been found that the material formed in the thermal impact zone is weaker than the base material under the influence of high parameters, or the newly formed joint metal contradicts the previously established statement about the increased hardness of this zone in the case of welded joints of low-alloy structural steels.

Practical significance

The results obtained in the Doctoral Thesis can be used by steel construction companies in the production of various metal structures. High-strength steel is one of the materials that manufacturing companies tend to avoid due to lack of knowledge about its properties and possibilities to process it. Such materials are increasingly being used to facilitate construction. While changes in technology other than the processing of low-alloy construction steels are leading to the abandonment of orders, which can lead to losses due to incorrect production.

Developing and presenting the obtained results to the companies of the steel manufacturing industry, as well as advising them on the possibilities of welding high-strength steels, would give them an advantage in the processing of such materials. It would also make it possible to reduce errors and eliminate the use of inappropriate technologies at the beginning of projects. The developed forecasting model is used in the production of Green Power Ltd products from high-strength steel (650 MPa), where it is necessary to significantly reduce the weight of the structure without losing its strength. This is confirmed by letter of Mārtiņš Grantiņš in Appendix 3.

In addition, in cooperation with the company *Speciāls Elektrods* Ltd, which is one of the leading distributors of MAG welding equipment Fronius® in Latvia, the study has been analyzed. Based on this analysis the solutions are evaluated and offered for metalworking companies in welding of high-strength steels. A letter confirming the cooperation is presented in Appendix 4.

The results presented for the defense

Results of experimental studies describing the correlation of the chemical composition and hardness of the weld between the welding parameters and the choice of shielding gas. In the performed experiments, welding parameters were chosen from 280 A to 320 A, but the shielding gas composition was chosen from 8 % to 25 % CO_2 mixtures with argon, as well as 5 % CO_2 and 5 % O_2 mixture with argon. With the increase of the percentage content of CO_2 gas, no significant changes in the alloyed elements were observed, as well as in the results of hardness measurements in the welded joint. With the decrease of CO_2 content, the decrease of alloying materials, as well as the decrease of the hardness of the indicated weld material was observed with the increase of welding parameters. As a result of the mixture of shielding gases containing 5 % CO_2 and O_2, the percentage of alloying elements in the weld was the lowest regardless of the welding parameters selected and set. No change or significant decrease in the indicated hardness was observed, regardless of the change in welding parameters.

A model developed for predicting the chemical composition and hardness of the welded joint, depending on the interaction of welding shielding gas and welding parameters. The interaction of the used shielding gas with the selected welding parameters under the conditions of spray-arc transfer significantly affects the hardness of the weld material. With the help of the developed model it is possible to predict the changes of hardness parameters (its stability or decrease) depending on the selected shielding gas and welding parameters.

A methodology developed for measuring and forecasting the strength of a welded joint depending on the choice of shielding gas and welding parameters. Using the methodology, the measurement results are within the absolute error limits. Using the developed methodology, the conformity assessment criteria of the forecasting model fall within the limits that indicate the development of a correct model. The methodology specifies guidelines for measurement procedures in the range of percentage of shielding gases from 8 % to 25 % CO_2 for the mixture, as well as 3 % to 7 % CO_2 and O_2 mixture in argon, and welding parameters from 260 A to 360 A.

Approbation of obtained results

Publication in a journal indexed in international databases

1. I. Boiko, D. Avisans “Study on Shielding Gases for MAG Welding”, Journal “Materials Physics and Mechanics”, Vol. 16, No 2 (2013), pp. 126–134, ISSN 1605-8119, SCOPUS, Chemical Abstracts, Elsevier Bibliographic Database.

Publication in conference proceedings

1. D. Avišāns, I. Boiko, “Защитные газы для MAG сварки: вопросы экономической эффективности”, Proceedings of 7th International Symposium “Surface Engineering. New Powder Composition Materials. Welding”, 2nd Part, 23–25 March 2011, Minsk, Belarus, pp. 226–232.

2. I. Boyko, V. Kulakova, D. Avisans, “New approach for modeling of the welding processes”, Proceedings of 15th International Research/Expert Conference “Trends in the Development of Machinery and Associated Technology” TMT 2011, Prague, Czech Republic, 12–18 September 2011, No. 1, pp. 809–812.

3. D. Avišāns, I. Boiko, “Review on Shielding Gases for Mag Welding of Mild Steel”. In: 12th International Symposium “Powder Metallurgy: Surface Engineering, New Powder Composite Materials. Welding”: Proceedings, Minsk, Belarus, 7–9 April 2021. Minsk: Belarusskaya Navuka, pp. 314–324. ISBN 978-985-08-2709-8.

4. D. Avišāns, I. Boiko, A. Avišāne, “Influence of 8 % CO_2 and argonshielding gas mixture on MAG welding of high strength steel (650 MPa) in spray-arc”, Proceedings of International Scientific Conference “Engineering for Rural Development 2022”, Jelgava, Latvia, 25–27 May 2022, pp. 936–942.

Publications in conference abstract books

1. D. Avišāns, I. Boiko, “Aizsarggāzes MAG metināšanā”, 50. RTU studentu zinātniskās un tehniskās konferences materiāli, 2009. g. aprīlī, Latvija, Rīga. – Rīgā: RTU Izdevniecība, 2009. g., 15. lpp.

2. D. Avisans, I. Boiko, “Study of the Shielding Gas Influence on Costs of the Welding Joint”, Book of abstracts of the 20th International Baltic Conference “Materials Engineering 2011”, 27–28 October 2011, Kaunas, Lithuania, ISSN 2029-8307, p. 56.

Participation in international conferences

1. I. Boyko, V. Kulakova, D. Avisans, "New approach for modeling of the welding processes", 15th International Research/Expert Conference "Trends in the Development of Machinery and Associated Technology", TMT 2011, Prague, Czech Republic, 12–18 September 2011.

2. D. Avišāns, I. Boiko, "Защитные газы для MAG сварки: вопросы экономической эффективности", 7th International Symposium "Surface Engineering. New Powder Composition Materials. Welding", 23–25 March 2011, Minsk, Belarus.

3. D. Avisans, I. Boiko, "Study of the Shielding Gas Influence on Costs of the Welding Joint", 20th International Baltic Conference "Materials Engineering 2011", 27–28 October 2011, Kaunas, Lithuania.

4. D. Avisans, "Shieldig gases in MAG welding: Economical issues", 8th International Conference MET-2013 Materials, Environment, Technology, June 19–20, 2013, Riga, Latvia.

Presentations in international conferences organised by Riga Technical University

1. D. Avišāns, I. Boiko, "Metināšanas ar kūstošu elektrodu aizsarggāzu vidē galvenie raksturojumi", 51. RTU starptautiskā zinātniski tehniskā konference, 2010. gada 11.–15. oktobris, Rīga, Latvija.

2. D. Avišāns, I. Boiko, "Metināšanas ar kūstošu elektrodu aizsarggāzu vidē galvenie raksturojumi", 52. RTU starptautiskā zinātniski tehniskā konference, 2011. gada 13.–16. oktobris, Rīga, Latvija.

3. D. Avisans, I. Boiko, "Study of the shielding gas influence on welding joint appearance", Riga Technical University 53rd International Scientific Conference dedicated to the 150th anniversary and The 1st Congress of World Engineers and Riga Polytechnical Institute/RTU Alumni, 11–12 October 2012, Riga, Latvia.

4. D. Avišāns, "Rsearch of welding by meltig electrodes in protective gas environment", 54the RTU International Scientific Conference, 14–16 October 2013, Riga, Latvia.

USED SYMBOLS AND TERMS

A – current in Amperes;

V – voltage measured in Volts;

m/min – melting electrode wire feed speed;

CO_2 – carbon dioxide;

O_2 – oxygen;

Ar – argon;

Mn – manganese;

Ni – nickel;

shielding gas – a mixture of gases containing argon, carbon dioxide, as well as oxygen, which provides protection of the weld from the influence of the environment during the welding process;

low-alloy high-strength steel – steel in which the composition of the alloying elements does not exceed 2.5 % and its minimum yield strength is reached at 450–750 MPa;

welding pool – an area created by metal and a melting electrode during welding, where the metal is in the liquid phase;

high welding parameters – welding current increased between 265 A and 365 A that insures the welding wire transfer in spray-arc mode;

spray arc – a mode of transformation of a molten electrode from a solid phase to a liquid before it comes into contact with the molten base material;

penetration – the shape and depth of the newly formed weld in the base material of the molten and then hardened metal alloy;

MAG (Metal Active Gas) – fusion electrode welding in an active shielding gas environment;

HAZ – heat affective zone, which reflects the area of the base metal that has not been melted under the influence of the electric arc, which has been exposed to high temperatures and as a result its physical and structural properties have changed.

1. LITERATURE REVIEW

1.1. Shielding gas influence on MAG welding process

Sshielding gas performs several functions during the MAG welding process. Its main function is to protect the welding pool from the influence of the surrounding atmosphere. After a review of several studies and literature sources, it has been concluded that shielding gas additionally performs the following functions being responsible for:

1) the formation of an electric arc and its stability [6]–[[8], [14], [22], [29], [36], [48];
2) metallurgical processes in the welding pool [5], [6], [29], [31], [38];
3) the composition of alloying materials in the welded seam [36], [38], [42], [46], [48];
4) the formation of pores and inclusions in the created seam [5], [30], [42], [48];
5) the formation of the weld seam shape and alloy [29], [36], [46], [55].

One of the main shielding gases, thanks to which the MAG process became widespread and available in the middle of the 20th century, was CO_2 [1]. On the other hand, in the last decade of the same century, mixtures of Ar and CO_2, as well as Ar and O_2, or mixtures of all three gases mentioned above, were actively used for the MAG welding process [14]. However, in recent years, several studies have been conducted and published on the effect of argon mixtures on the welding of various materials in a shielding gas environment, and relatively contradictory results have been obtained.

Various studies have emphasized that as the CO_2 content increases, the number of pores and various inclusions in the weld increases [30], [36]. In contrast, there are several publications that claim the opposite [5], [29].

1.2. Effect of welding wire material, base material and welding parameters on the MAG welding process

The studies of recent years also reveal a significant difference in the effect of shielding gas composition on welding of low-alloy steels with different yield strengths. For structural steels with a minimum yield strength of 235–355 MPa, a 25 % mixture of Ar and CO_2 is mentioned as one of the best shielding gases [5], [29]. On the other hand, in a study on welding of materials with a yield strength of 900–1000 MPa, a shielding gas with a lower CO_2 content in Ar is mentioned as the best solution [38], [42]. It should be mentioned that the above studies were carried out using welding with a monolithic melting wire electrode. However, the used current parameters differ. For example, several studies use short arc parameters for materials of the first type, where the melting wire electrode is melted in the form of drops in the welding pool [5], [6], [30], [31], [36]. In contrast, in studies of 900–1000 MPa materials in welding, this transition occurs in the form of a spray-arc parameters [38], [42], [46]. In a study examining the effect of shielding gases on the welding of low-alloy structural steels, a flux-cored melting wire electrode is used [29]. Its transfer in the welding pool is provided in the form of a spray-arc at significantly reduced current parameters.

In addition, some sources were investigated where flux-cored wire is used, which provides a self-shielding effect but does not use a shielding gas [43]–[45]. These studies examine and describe the influence of alloying materials on the mechanical properties of the weld.

1.3. A compilation of experiments conducted by researchers

The summary of the conducted studies was combined in one table showing the technology used in the conducted research experiments, the source of information where the study is described, the used metal, shielding gas and welding parameters. The table also describes what has been studied, the results obtained in the experiments, and the conclusions drawn.

In summary, it can be concluded that various studies have been conducted on the effect of shielding gas on carbon steels such as S235, S275, and S355, which are standard structural steels. A couple of studies without the use of shielding gas have been devoted to the strengthening of standard structural steel welds using an alloyed melting electrode. Low-alloy steels whose yield strength reaches 850–1000 MPa are also examined. These studies are carried out by many authors using high welding parameters.

Therefore, it was concluded that structural steels in the range of 420–850 MPa are not considered, even though these materials are currently used more often in production, helping to lighten the weight of structures, ensuring their sufficient strength.

The above conclusions open the possibility for a new research on the effects of shielding gas on high strength steel (650 MPa) with MAG welding technology. Taking into account the previously studied, a decision was made to conduct the research by welding with high welding parameters.

Table 1.1

Summary of Reviewed Literature Sources

Experiment	Reference	Metal	Shielding gas	Welding parameters	Mechanical properties	Chemical composition	Developed model
MAG + solid wire	Kah [5]	S235	Ar + 2.5 % CO_2, Ar +10 % CO_2, Ar + 18% CO_2, Ar + 25% CO_2	Short arc	Pore size and quantities	?	?
MAG + solid wire	Knovel [6]	S235	Ar + 5 % CO_2 + 5 % O_2, Ar + 20 % CO_2, 100 % CO_2	Short arc	Charpy test	?	?
MAG + flux-cord wire	Gadallah [29]	S235	100 % Ar, 100 % CO_2, Ar + 5% CO_2, Ar + 10 % CO_2, Ar + 18 % CO_2, Ar + 20 % CO_2, Ar + 25 % CO_2	Puls-arc	Charpy test not for all samples 100 % Ar, Ar + 25 % CO_2	Microstructure	?
MAG + solid wire	Moreira [30]	S235	100 % Ar, Ar + 8 % CO_2, Ar + 15 % CO_2, Ar + 25 % CO_2	Short arc	Pore size and quantities	?	?
MAG + flux-cord wire	Çevik [31]	S275	100 % Ar, Ar + 12 % CO_2 + 2 % O_2	Short arc	Tensile strength, spatter	Microstructure	?
MAG + solid wire	Boiko [36]	S235	Ar + 8 % CO_2, Ar + 18 % CO_2, Ar + 25 % CO_2, 100 % CO_2	Short arc	?	Chemical composition	Model of economical calculation
MAG + solid wire	Gouda [38]	S950	100 % Ar, Ar +10 % CO_2, Ar + 15 % CO_2, Ar + 20 % CO_2, Ar + 25 % CO_2	Spray-arc	Charpy test, hardness	Microstructure, chemical composition	?
MAG + 3 solid wires	Peng [40]	S890	Ar + 20 % CO_2	Spray-arc	Yield and tensile strength, hardness	Microstructure	?
MAG + solid wire	Zhao [41]	S355J2 + N	Ar + 18 % CO_2, Ar + 13 % CO_2 + 3 % O_2, Ar + 10 % CO_2 + 3 % O_2, Ar + 4 % CO_2 + 3 % O_2	Puls-arc	Penetraiton size and form, hardness	Microstructure	?
MAG + solid wire	Tongbang [42]	S1000	Ar + 5 % CO_2 + 5% O_2, Ar + 10 % CO_2, Ar + 20 % CO_2, Ar + 30 % CO_2	Spray-arc	Yield and tensile strength, hardness, Charpy test, pores	Microstructure, chemical composition	?

Table 1.1 continued

Experiment	Reference	Metal	Shielding gas	Welding parameters	Mechanical properties	Chemical composition	Developed model
SMAW + 3 flux-cord wires	Keehan [43]	S1000	?	Spray-arc	Yield and tensile sStrength	Microstructure	Model of structure formation depending on Mn and Ni content
SMAW + flux-cord wire	Lord [44]	S460	?	Spray-arc	Yield strength, Charpy test	?	?
SMAW + flux-cord wire	Kang [45]	S355	?	Spray-arc	Yield strength, Charpy test	?	?
MAG + 2 solid wires (1.6 mm)	Francis [46]	L485	100 % Ar, Ar + 1 % O_2, Ar + 2 % O_2, Ar + 3 % O_2, Ar + 4 % O_2, Ar +5 % O_2, Ar + 10 % CO_2, Ar + 14 % CO2, Ar + 23 % CO_2, Ar + 28 % CO_2, Ar + 52 % CO_2, Ar + 75 CO_2, 100 % CO_2	Spray-arc	Penetraiton size and form	Microstructure, chemical composition	Diagramm of creation of structure as a function of Mn and O content

2. EXPERIMENTAL STUDIES

2.1. Materials and methods of investigation

Considering the reviewed literature and technological provision, welding experiments which were closer to real production conditions were carried out. Considering the analysis of the literature, in order to use it successfully, it should be ensured that the human factor cannot affect the progress of the welding process and the trajectory of the movement of the welding torch should be smooth and controlled, and that the environmental conditions that affect the welding process are fully ensured. As it was mentioned before the base metal that was chosen for the experiments was 650 MPa class steel. In this case STRENX®650MC delivered by company SSAB was taken to create the samples for welding experiments. The chemical composition of the material that was tested in the laboratory was different than the one given by the producer (see Appendix 1). The results after testing by optical spectrometer are given in Table 2.1.

Experimental materials

STRENX®650 grade 10 mm thick material was chosen for the research experiments, the chemical composition of it is given in Table 2 and it was cut into equal 100 x 200 mm samples. They were put together to form a T-joint. Then, with two spot-welded seams on the opposite side of the seam a rigid welding sample was created for the further welding experiment. No additional preparation was done of any of experimental samples (no beveling on welding side).

Experimental equipment and conditions

Welding equipment of company FRONIUS® TPS500i (Fig. 2.1) and welding tractor Fronius® FlexTrack 45 Pro (Fig. 2.2) was used to create smooth movement of the welding torch and regular welding joint.

Fig. 2.1. Welding machine Fronius®MIG500i [49].

Fig. 2.2. Welding tractor Fronius® FlexTrack 45 Pro.

A welding wire electrode was used according to the characteristics of the base material with a higher manganese (Mn) content. The chemical composition of the welding wire is given in Table 2.1. The diameter of the electrode was chosen to be

1.2 mm, which provides greater transfer of the melting electrode. It also makes it possible to increase the welding speed, which helps to reduce heat input during the welding process.

Table 2.1

Composition of Base and Filling Material

	C	Si	Mn	S	Cr	Mo	Ni	Al	Nb	Ti	V
Base material	0.0581	0.157	1.56	0.0162	0.0451	<0.0030	0.0251	0.0191	0.0416	0.102	0.0165
Electrode wire	0.075	0.63	1.63	0.007	0.28	0.22	1.42	0.006	0.002	0.001	0.09

Welding process was done according to EN ISO 6947 in PB (Plate Horizontal Vertical) position and a welding seam was created with a height of 5 mm (*a* = 5). Figure 2.3 shows the welding setup of the experiments.

Fig. 2.3. Welding setup of the experiments.

Argon mixtures with different percentages of CO_2, as well as Argon + CO_2 + O_2, were used in the study. The composition of these gases is specified in Table 2.2 and can be found in Appendix 4.

Table 2.2

Composition of Shielding Gases

Gas	Argon	CO_2	O_2
MISON®25 (M25)	75 %	25 %	–
MISON®18 (M18)	82 %	18 %	–
MISON®8 (M8)	92 %	8 %	–
CORGON®3 (C3)	90 %	5 %	5 %

The choice of shielding gases is justified by their wide use in metal processing companies in Latvia as well as in other European countries and beyond. The permissible humidity in its composition is also essential for selecting the gas – max 10 ppm. Its flow was ensured at 15 l/min, and flow control was performed before starting each experiment with all samples.

The welding parameters in the study were set to achieve jet transfer arc modes: 280 A at 28 V, 300 A at 29 V, and 320 A at 30 V. For each block of experiments, the travel speed of the welding torch was set accordingly: 350, 380, and 420 mm/min. The matrix of welding parameters was selected using a special welding modeling program WeldConnect® (Fig. 2.4)

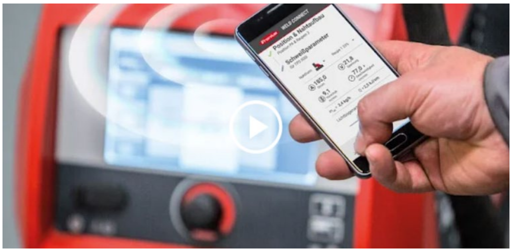


Fig. 2.4. WeldConnect® application [50].

Arc stability was checked after setting the welding parameters before each block of experiments (at 280 A/28 V, 300 A/29 V and 320 A/30 V). The projection of the welding wire electrode from the welding tip was set at 19 mm before each welding experiment was performed.

Experimental conditions

For welding with a melting electrode in a shielding gas environment, it is important to provide a closed space where drafting wind is not possible. It can negatively affect the welding process and create pores in the welded seam. The room temperature was kept constant at 20 ºC, also ensuring a constant temperature of the material samples. All the samples intended for welding were stored in the room for several days before the experiments were carried out.

During welding, various welding aerosols are released, which can affect both welders and personnel supervising the welding process. An air recirculation and purification unit were used for this purpose.

2.2. Results of the investigation

After conducting the experiments, all the welded samples were photographed and cut with a band saw into 10 mm thick samples. The edges were then cut on all sides to prepare small samples in which only a cross-section of the weld can be seen, which can be pressed into molds and prepared for grinding and polishing [51], [52]. After grinding and polishing the samples, they were etched with 9 % nitric acid liquid, which gave the opportunity to see the fusion form of the welded joint or the penetration.

Spatter formation on welding seam

After obtaining the photographs, it was possible to make a visual assessment of the welded seam. One of the important visual assessments is the amount of spatter created by the melting electrode on the base material (Fig. 2.5).

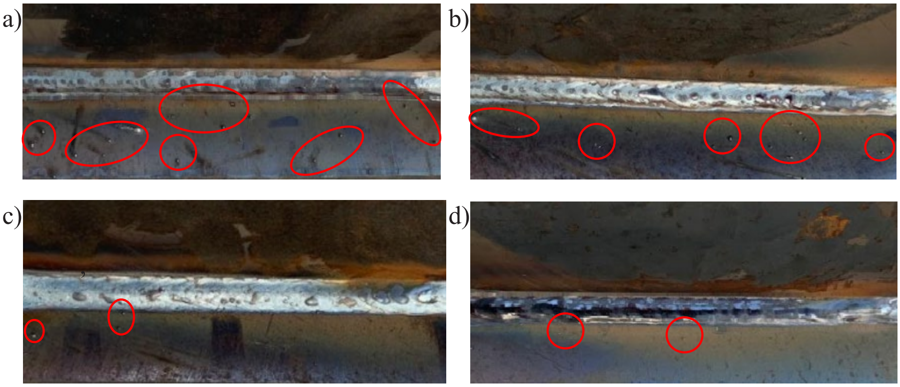


Fig. 2.5. Amounts of spatter on welding seams with different shielding gases welded at 300 A parameters: a) M25; b) M18; c) M8; d) C3.

There was more spatter on the samples welded with shielding gases M25 and M18 at all of welding parameters. According to previous studies [36], [47], CO_2 gas provides and supports creation of short arc. The increase of its content in argon mixture increases the possibility of spatter creation. It appears that the influence of CO_2 still gives the possibility to create a short arc at high welding parameters. This leads to appearance of spatter after welding with these two shielding gases.

An interesting phenomenon was observed on the welding seam where mixture C3 was used (Fig. 2.6).

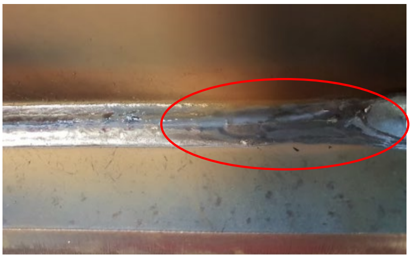


Fig. 2.6. Phenomenon of SiO_2 on the welding seam.

A layer of thin and transparent substance was covering the welding joint all across it. It appears to be the SiO_2 (siliceous oxide or glass) layer. The siliceous that was burned out from the welding pool made a reaction with oxygen that was in the shielding gas and brought it to the upside of the welding joint.

Shape of penetration and form of welding seam

After preliminary preparation, grinding, polishing and treatment of all samples with nitric acid liquid, it became possible to evaluate the shape of the welded joint, determine its dimensions and the form of penetration.

A smooth shape of the seam, with little reinforcement, as well as a stable shape of the penetration was obtained using mixtures M25 and M18 (Fig. 2.7 a), b), c), d), e), f)). As the welding parameters increase, the formation of reinforcement in the lower zone of the seam can be observed. This was caused by the higher temperature during the welding process at a higher wire feed, which contributed to the slippage of the weld pool. A good combination of penetration and weld seam shape was achieved with samples welded with M8 shielding gas at 280 A and 300 A parameters (Fig. 2.7 g), h)). Although a slight slippage of the welding pool can be observed at the 280 A mode, the reinforcement has been formed regular in the middle of the seam along its entire length. The shape of the through-melt became uneven when the welding parameters were increased to 320 A using the same shielding gas M8 (Fig. 2.7 i)). With the combination of the same parameters and shielding gas, it was clearly possible to observe the formation of the so-called “Aagon finger” in the seam.

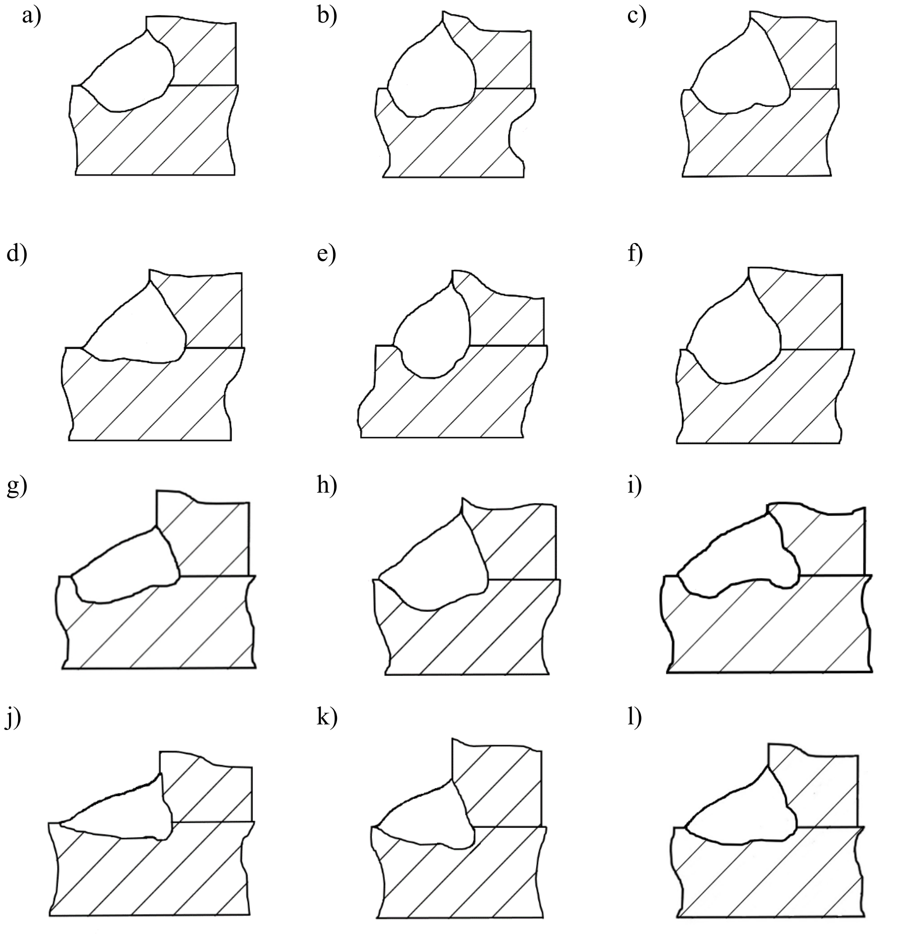


Fig. 2.7. Welding seam form and shape of Penetration of the welded samples: M25 – a) 280 A, b) 300 A, c) 320 A; M18 – d), e), f); M8 – g), h), i); C3 – j), k), l).

Irregular penetration and form of the seam and slippage of the reinforcement were observed for all samples welded with the C3 mixture (Fig. 2.7 j), k), l)). This can be explained by the higher temperature of the weld pool, which resulted in the melting of the base material not only where the melting wire electrode was pointed but also on the horizontal base plate in the direction away from the corner. Because of this, the side plate of sample 280 A was almost unmelted.

2.3. Investigation of Microstructure

Microstructure of all welded samples was captured by optical microscope Axiovert 40 MAT. One of the defects that can be recognized at 50 times (50 x) increase of the picture are the pores and inclusions in the welding joint. With a magnification of 200 times, it is possible to examine the microstructure of the newly created weld seam in finer detail.

Pores and inclusions

According to Fig. 2.8, it appears that more inclusions were captured in welding joints that were welded with M25 and C3 shielding gases.

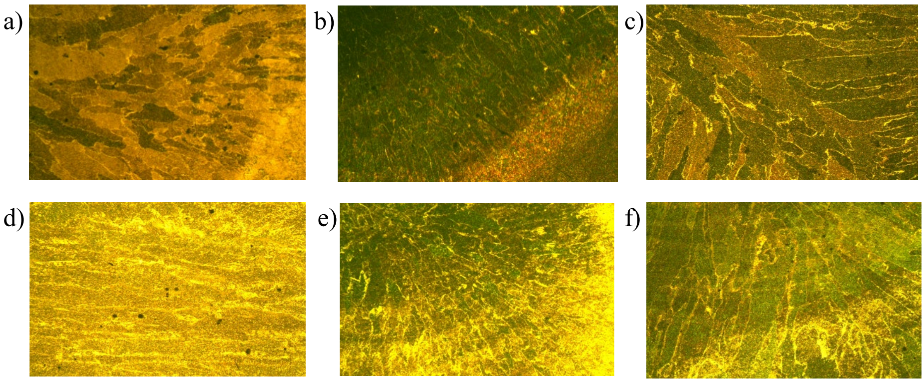


Fig. 2.8. Welding seam microstructure (50 x) from samples welded with M25 and C3 shielding gases: a) M25 – 280 A; b) M25 – 300 A; c) M25 – 320 A; d) C3 – 280 A; e) C3 – 300 A; f) C3 – 320 A.

Smaller amount and smaller size of the inclusions were found in welds that were made with mixture M18 (Fig. 2.9).

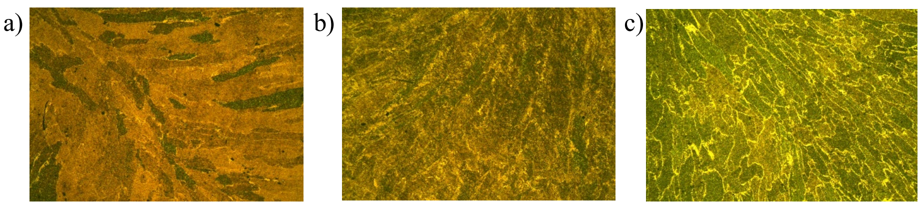


Fig. 2.9. Welding seam microstructure (50 x) from samples welded with M18 shielding gas: a) M18 – 280 A; b) M18 – 300 A; c) M18 – 320 A.

The least amount of inclusions but with a little bigger size appeared in welds that were welded with M8 shielding gas (Fig. 2.10).

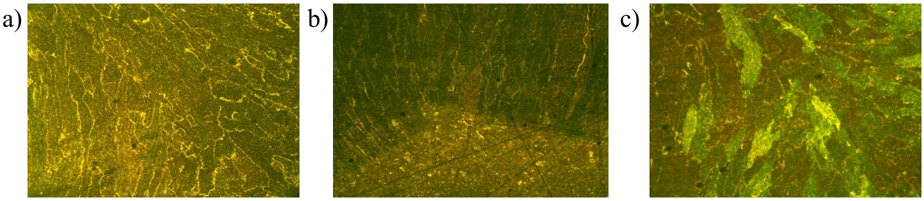


Fig. 2.10. Welding seam microstructure (50 x) from samples welded with M8 shielding gas: a) M8 – 280 A; b) M8 – 300 A; c) M8 – 320 A.

The formation of inclusions and pores in the samples welded with a shielding gas with a higher CO_2 content (M18 and M25) and with a shielding gas containing O_2 (C3) can be explained directly by the increased influence of O_2 on the welding process. It constantly flows directly into the liquid metal weld pool in an increased volume, which quickly solidifies as a result of the increased welding speed. As a result, O_2, which actively reacts with various alloying materials, simultaneously creating oxides and also being released in gaseous form, does not reach the surface of the seam. This phenomenon is described in M. Gouda's research on the welding of 950 MPa strength steels, where an increased O_2 content in the shielding gas is also indicated [38].

Microstructure

In several welding studies of high-strength steels (950–1000 MPa), much attention is paid to the structure of the microstructure of the welded seam [38], [40], [42], [43]. The size of their grains, as well as their arrangement, is examined and evaluated.

In the images taken by the optical microscope (with 200 times magnification), it is possible to see the size, shape and arrangement of the grains of the created seam structure. The grain size of the metal structure can affect the strength of the metal and the formation of various types of defects [59].

According to the conducted experiments, it can be concluded that the structure of finer ferrite and pearlite grains is formed in samples M25 320 A and M8 280 A (Fig. 2.11). Several formations of wider and longer ferrite grains can also be observed in the structure formed by M25 320 A [62].

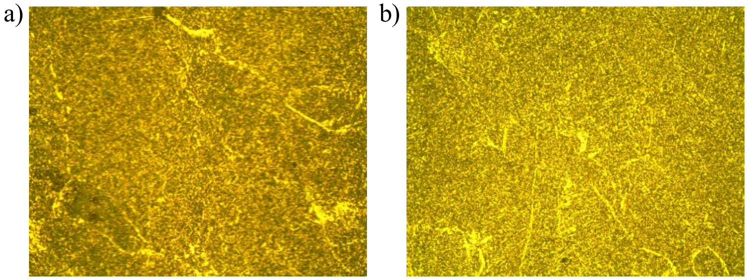


Fig. 2.11. Material microstructure (200 x): a) M25 320 A; b) M8 280 A.

In the microstructure of samples M8 280 A, these grain formations are much thinner and shorter, thus the structure is more even and ensures the strength of the welded joint [62].

For several welded samples, such as M25 300 A, M18 320 A, M8 300 A, M8 320 A, and C3 320 A, uneven formation of martensite and ferrit-perlit formations with ferrite grain boundaries can be observed in the welded joint structure (Fig. 2.12). As can be seen, such a structure is formed at higher welding parameters, which can be explained by faster cooling of the samples and the occurrence of metallurgical processes in the joint [63]. Such created martensite boundries may cause cold cracks in the weld [59], [62].

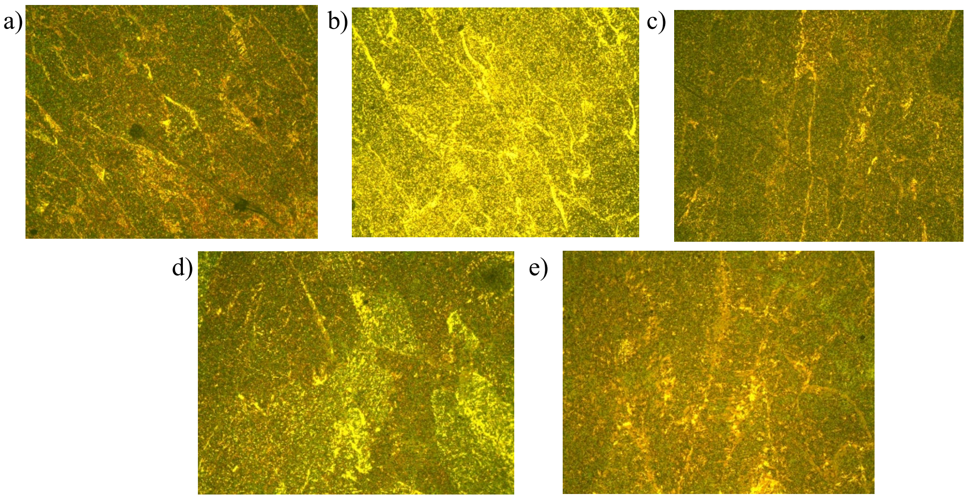


Fig. 2.12. Material microstructure (200 x): a) M25 300 A; b) M18 320 A; c) M8 300 A; d) M8 320 A; e) C3 320 A.

Similar structures have formed in samples M25 280 A and M18 280 A (Fig. 2.13). The grain size of the microstructure is small, but martensite formations are placed with uneven distance between each other. This may cause the formation of different internal stresses in the weld [62].

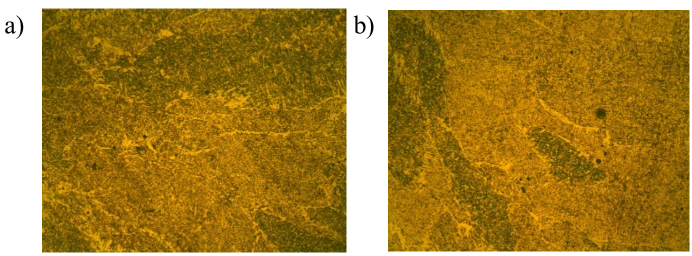


Fig. 2.13. Material microstructure (200 x): a) M25 280 A; b) M18 280 A.

In the microstructure of the welded samples C3 280 A, C3 300 A and M18 300 A, the grains form elongated shapes and form regular layers, which are separated by grain ferrites (Fig. 2.14). All these structures are with regular form however, the elongated grain shape of the stratification may adversely affect the strength properties of the weld metal [60].

a) b) c)

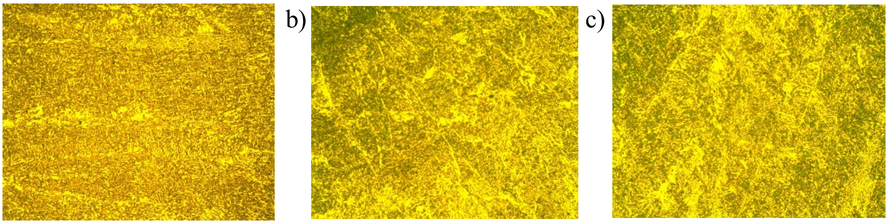


Fig. 2.14. Material microstructure (200 x): a) C3 280 A; b) C3 320 A; c) M18 320 A.

As it can be observed from Fig. 2.14, more ferrite grains are formed. As per literature sources [61], [62], this can make the welding joint more fragile and may influence the formation of intercrystal or laminar cracks.

2.4. Chemical composition

Using the optical emission spectrometer PMI-MASTER Pro2, the chemical composition of all welds was investigated. Shielding gas can affect the amounts of alloying elements that can be burned out of the weld, as found in previous studies [36].

Manganese (Mn) is one of the most important alloying elements that ensures the high strength properties of welded joints [54]. Its percentage changes in the chemical composition of the welded seam depending on the effect of shielding gas and welding parameters were determined after measurements with an optical emission spectrometer. The graph in Fig. 2.15 shows the changes in Mn content in the welding joint with each gas at all three welding parameters.

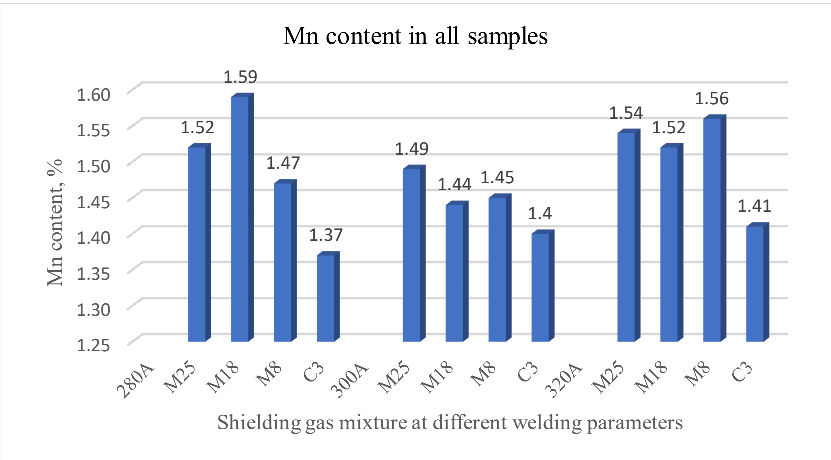


Fig. 2.15. Chart of Mn content in welding joints with different shielding gases at different welding parameters.

The chemical composition of the welding wire was determined using the certificate provided by the manufacturer. The chemical composition of the base material was checked using an optical emission spectrometer. The obtained results were compared with the obtained results from a certain chemical composition of the welded seam with an optical emission spectrometer.

As discussed and established in previous studies, more alloying elements were burned from welding joint that were welded using shielding gas mixture C3 and short arc parameters [14], [36]. A similar result was also observed in this study. The Mn content decreases by more than 16 % compared to the wire electrode and more than 12 % compared to the base material.

A better and more stable result, where the percentage of Mn did not decrease significantly, was observed in the welds made with shielding gas mixture M25. With this mixture, a reduction of 6–9 % vs. wire and 1–4 % against base material was observed in all three selected welding parameters.

The smallest reduction against the chemical composition of the molten electrode wire material (only 2 %) and a steady increase against the chemical composition of the parent material was observed in the samples welded with M18 alloy at 280 A. At 300 A parameters, this mixture showed a greater drop in Mn content (12 % vs. wire; 8 % vs. parent material).

As the parameters increased to 320 A, the shielding gas mixture M8 showed the best result in this study. The manganese content of these welded joints decreased by only 2 % compared to the wire material and did not change compared to the base material. At lower parameters, this mixture showed lower Mn content in the weld joint (10–11 % vs. wire; 6–7 % vs. parent material).

As indicated in several studies, Ni content in high-strength steels also affects its mechanical properties [42] – [45]. The base material of the used fusible electrode wire also has a higher Ni content compared to the base material. Consequently, the content of this alloying element was also measured depending on the shielding gas used and the welding parameters (Fig. 2.16).

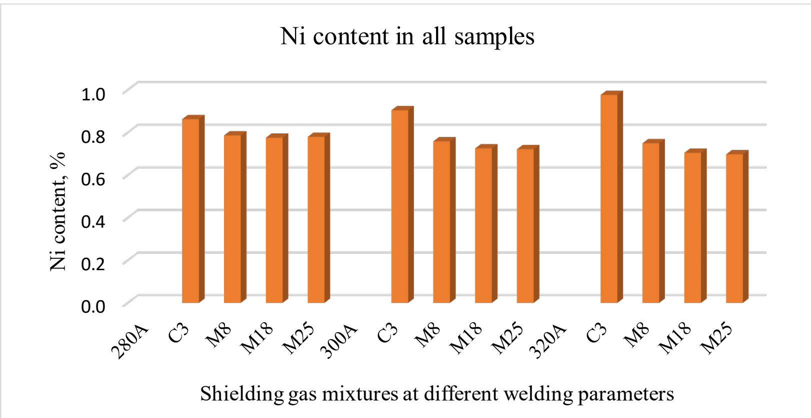


Fig. 2.16. Chart of Mn content in welding joints with different shielding gases at different welding parameters.

Unlike Mn, the percentage content of which significantly decreased in the welded seam under the presence of O_2 shielding gas, the content of Ni was the highest among all welded samples. It is important to emphasize the observed phenomenon that the Ni content increased with increasing welding parameters (by 14 % between 280 A and 320 A).

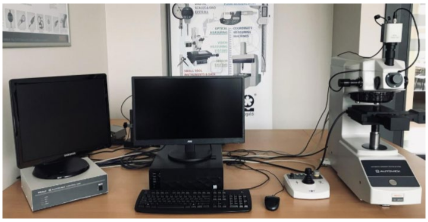
Contrary to the samples welded with the C3 mixture, the Ni content decreased in the samples welded with all shielding gases containing CO_2. A more significant reduction was observed for mixtures M18 and M25 and with increasing welding parameters (up to 10 %). This could be explained by the increased arc temperature during the welding process, which increases the possibility of burning Ni, as an alloying material, from the weld and under the influence of the previously observed and described possible short-circuit occurrence. For mixture M8, the change in Ni composition was not so significant (4 %).

It can be concluded that there has been an opportunity to view and create a relationship between the influence of O_2 and welding parameters on the content of Ni in the welded seam depending on the changes in welding parameters.

2.5. Hardness

High strength steel is mainly used for its properties. One of the main features that influences the material toughness is the hardness. It is important to keep this property in the welding joint as high as possible to the base metlas also after welding. All welded samples were tested with automated hardness testing machine Mitutoyo Micro Vickers hardness tester HM-210D (Fig. 2.22 a)) according to standard EN ISO 9015-1 procedures.

a)



b)

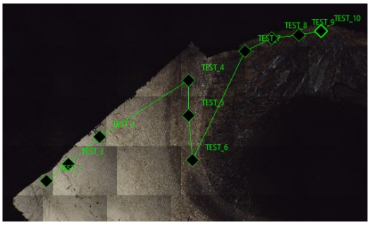


Fig. 2.22. Hardness testing setup: a) Mitutoyo Micro Vickers hardness tester HM-210D; b) hardness testing technology.

The welding joint was devided in the middle in the same way as it was done in one of the previous studies [41]. Ten stitches one by one after 0.5 mm were made into every sample covering base material (3 stiches), HAZ (3 stitches) and weld metal (4 stiches) (Fig. 2.22 b)). The changes in hardness of the material after welding are described in the chart in Fig. 2.23.

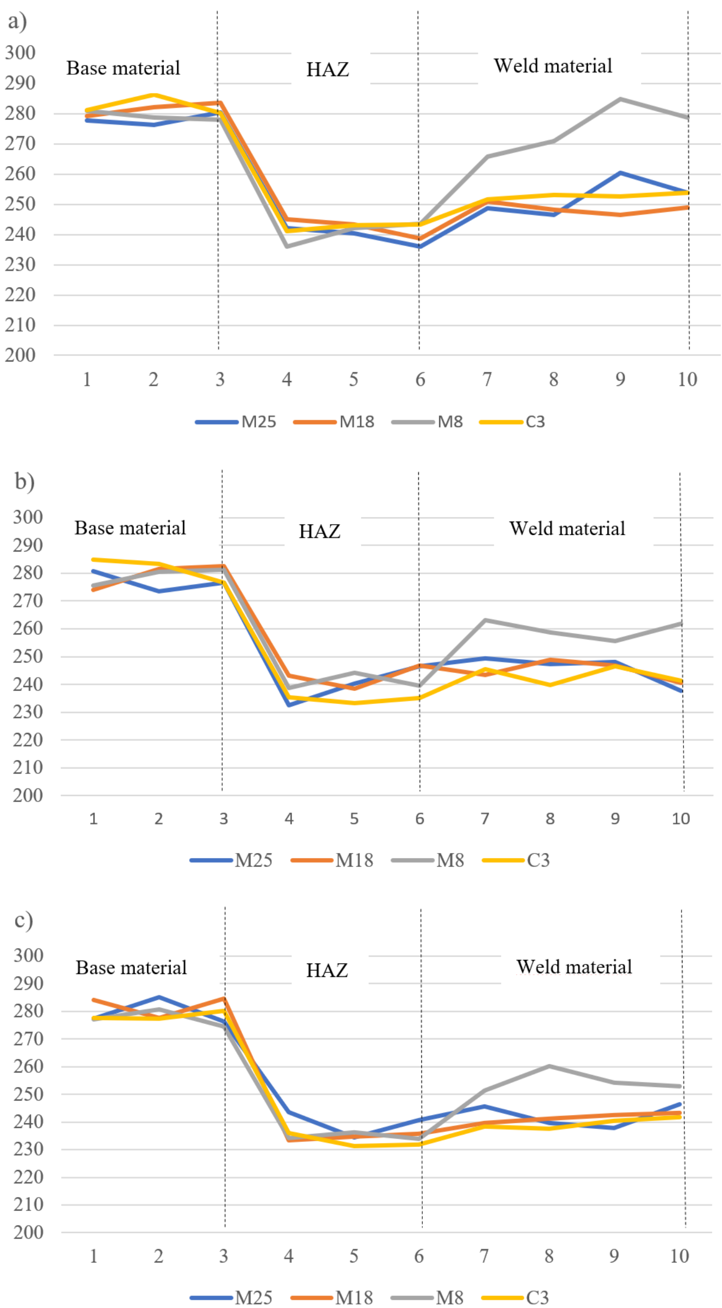


Fig. 2.18. Weld metal hardness at different welding parameters:
a) 280 A; b) 300 A; 320 A.

Each parameter set was highlighted separately in the graph that shows the tested hardness of the samples. From these graphs it appears that the hardness in HAZ is almost the same for every welded specimen. The difference is visible only in the welding pool. Hardness was the highest in samples welded with M8 shielding gas. Other Ar + CO_2 mixtures (M18 and M25), as well as the C3 mixture, showed smaller values of hardness in the welding seam. Similar results, where these hardness values are not as high, can also be observed in the samples welded with the C3 mixture. It is with this mixture that similar values can be observed for all three parameters used.

It was also possible to see that in one part of the welding pool at 280 A parameters the hardness was reached similar to that of base metal. This sample was welded with M8 shielding gas. Hardness close to the base metal was also reached at 300 A regime. As the parameters were rising, the hardness of the weld did not reach the same values as the base metal but still showed higher level than it was reached with other gases.

It is also possible to see that the HAZ of all welds made with gas mixtures M18 and M25 was a little bit longer than for other two shielding gases. It was approximately 1–1.5 mm wider compared to other samples. It can be explained with the CO_2 increase in shielding, as that supports the creation of short arc during the welding process.

3. A MODEL DEVELOPED FOR FORECASTING ALLOYING ELEMENTS AND HARDNESS OF THE WELDED SEAM MATERIAL

In order to compile the data and to find the relationship between the obtained result and the predicted content of alloying materials in the welded seam and its hardness, the obtained research results were collected by summarizing them in different graphs (Figs. 2.15, 2.16, and 2.18). A mathematical model for data prediction (Fig. 3.1) was developed with the help of the Microsoft Excel computer program, and it was also tested. Additional testing and model comparison was performed using the SPSS®Statistics computer program. The obtained results are reflected in Table 3.2.

3.1. A model for forecasting the relationship between shielding gas, welding parameters and changes in the composition of percentage of alloying elements Mn and Ni

After analyzing the literature, it was concluded that previous studies have paid attention to changes in Mn content in the welded joint [36], [38], [42], [46]. R. E. Francis in his work has also created a diagram that reflects the dependence of Mn on the content of oxygen content in the shielding gas [46]. Judging from the results of this study (Fig. 3.1 a)), it can be concluded that the results obtained in this study do not exactly coincide with the changes of the previously developed diagram at the parameters of 280 A and 300 A, whereas they coincide with the parameters of 320 A (Fig. 3.1 b)). Therefore, it can be concluded that the Mn content is affected not only by the CO_2 content in the shielding gas but also by the welding parameters. The simultaneous effect of these two relationships on Mn content has not been studied.

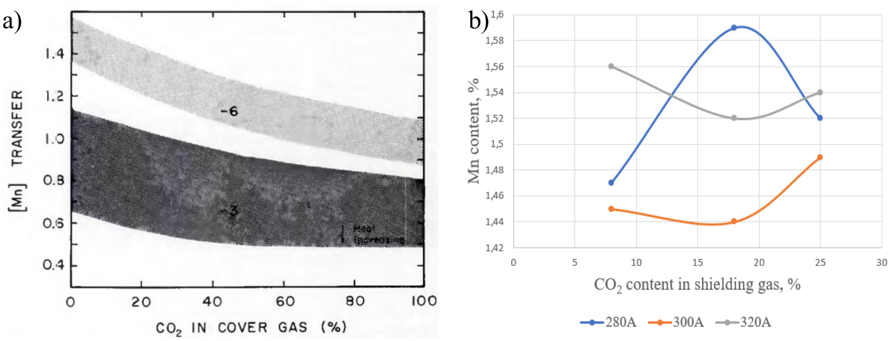


Fig. 3.1. Diagram of dependence of Mn on the composition of CO_2 in the shielding gas: a) the studied model [46]; b) data obtained in this study.

After reviewing the above-mentioned studies, it was decided not to create a separate mathematical model, which could be used to predict changes in the percentage composition of Mn and Ni depending on the composition of the shielding gas and the choice of welding parameters, because similar studies have been carried out previously.

3.2. A model for forecasting the relationship between the composition of shielding gas percentage, welding parameters and the hardness of the welded joint material

For the development of the forecasting model, the data obtained in the experiments of the Doctoral Thesis, which can be found in the full version of the Thesis, were used. Evaluating the obtained relationships between the welding current (Iw), the percentage of CO_2 and O_2, it can be concluded that they are most closely described by the straight line equation. A regression equation was created taking into account the observed trends. The model is still considered linear even though it contains non-linear relationships for the independent variables because the regression coefficients are linear [65]. The multivariate regression model is built as follows:

$$HV_w = a_{CO_2} \cdot CO_2 + a_{O_2} \cdot O_2 + a_I \cdot I_w + b, \tag{3.1}$$

where

HV_w – hardness of the weld metal;

$a_{CO_2,} a_{O_2,} a_I$ – regression coefficients;

I_w – welding current (A);

O_2 – oxygen content in welding protective gas (%);

CO_2 – carbon dioxide content in welding protective gas (%);

b – independent coefficient.

The Thesis used the Microsoft Excel computer program, which can also be replaced with other statistical programs, such as MatLab, MiniTab, etc., to calculate regression coefficients $a_{CO_2,} a_{O_2,} a_I$. In the computer program, the coefficients were calculated according to the method of least squares [65]. The obtained coefficients are placed in Formula (3.1), thus obtaining:

$$HV_w = (-1.02) \cdot CO_2 + (-3.74) \cdot O_2 + (-0.32) \cdot I_w + 364.31. \tag{3.2}$$

The obtained equation was checked for conformity. To do this, the correspondence of the calculated values of multivariate regression to the measured ones was analyzed using the corrected coefficient of determination, taking into account the number of independent variables and the number of measurements [65]:

$$\bar{R}^2 = 1 - (1 - R^2)\frac{n-1}{n-p-1'} . \tag{3.4}$$

As a result, the corrected coefficient of determination $\bar{R}^2$, taking into account the number of independent variables and the number of measurements, was determined to be $\bar{R}^2 = 0.70$. It shows a fairly close relationship between the calculated values and the measurement results, that is, 70 % of the measurements can be explained by the linear regression model used.

Using the aforementioned computer program with the method of analysis of variance (ANOVA – Analysis of Variance), the statistical significance of an empirical forecasting model was evaluated, which indicates the significance of the obtained coefficients of the mathematical model. The obtained results were summarized in Table 3.1.

Table 3.1

Conducted *t* and *P* Values

	CO_2	O_2	I_w	*b*
t	7.25	7.24	6.13	23.09
P	4.79E–09	5.02E–09	2.2E–07	3.16E–26

If the *P*-value of the regression equation does not reach 0.05 according to Fisher's criterion test, then the developed regression model is statistically significant or the data are reliable [65], [66]. As can be seen in Table 3.1, the obtained *P*-values for the multivariate regression model are significantly lower than the above-mentioned figure, from which it can be concluded that the obtained mathematical model is significant and reliable.

In order to compare the values of the experimental measurements and the obtained mathematical model, Fig. 3.2 was created.

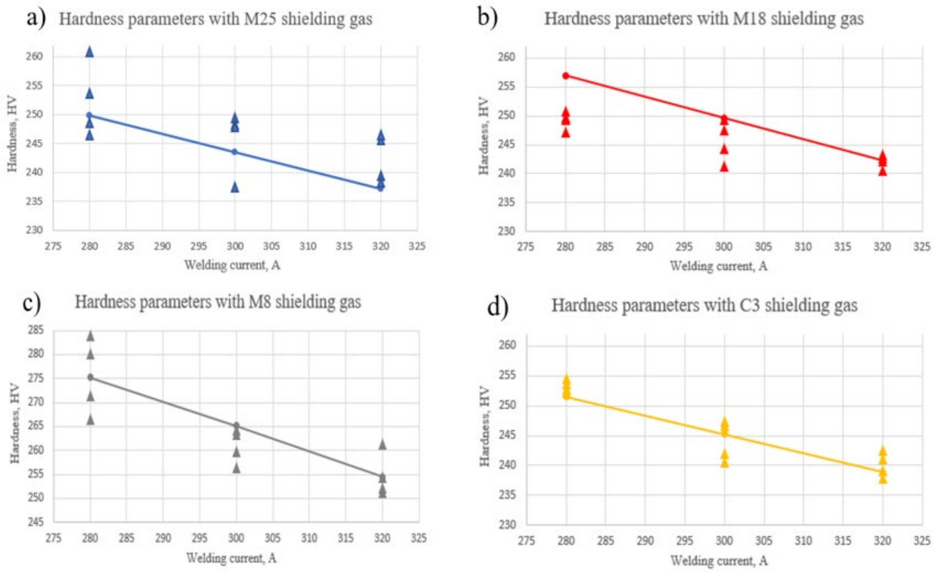


Fig. 3.2. Comparison of the calculated hardness of the welded seam material with the experimentally measured data: a) M25; b) M18; c) M8; d) C3.

It can be concluded that the generated model (3.2) shows quite accurate calculated results, which makes it possible to predict the hardness parameters of the welded metal, since the calculated tolerance of the model was 6 HV hardness units. This is the same tolerance that was found for the samples in the process of measuring both the base material and the weld material.

Additional testing of the obtained model was performed with computer program SPSS®Statistics. After collecting all the data and entering it into the data processing program, the following results were obtained (Table 3.2).

Table 3.2

Data and Coefficients Obtained with *SPSS®Statistics*

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	364.310	15.776		23.093	.000	332.517	396.104					
	ampers	-.318	.052	-.508	-6.126	.000	-.422	-.213	-.508	-.678	-.508	1.000	1.000
	co2_perc	-101.781	14.023	-.795	-7.258	.000	-130.042	-73.520	-.277	-.738	-.602	.575	1.740
	o2_perc	373.885	51.612	-.793	-7.244	.000	-477.902	-269.868	-.275	-.738	-.601	.575	1.740

a. Dependent Variable: hardness

From the data obtained in the first column, it can be concluded that they are similar to coefficients in Formula (3.2). A similar result can be found in the fourth column of the table, where the values of the *t*-distribution are identical to the previously calculated model are shown.

Since the created models look similar, and also the created graphs show very close results to the experimentally achieved ones, it can be concluded that the obtained mathematical model is correct and significant.

4. VALIDATION OF THE FORECAST MODEL AND DIRECTIONS FOR FURTHER RESEARCH

In cooperation with companies *Speciāls Elektrods* Ltd and GPower Ltd, we were working on the technology of manufacturing telescopic masts of mobile telecommunication antennas. One of the most important sections in this project was to develop the assembly structure of the mobile module mast. It was most important to decrease the weight of the mast structure itself without reducing the strength of the structure. For this reason, it was decided to use high-strength steel (class 650 MPa), as well as to use a hexagonal structure instead of a square one. In order to reduce the cost of the project, it was decided to make this structure with one welding seam.

It is essential to avoid deformations caused by welding in the manufacture of such a structure. One of the solutions is welding with higher speed and less thermal effect. To ensure this, it is necessary to use welding process with increased welding parameters, i.e. spray arc.

Using the developed model and the available materials, the first experiments have been carried out, thanks to which the first results and the first conclusions have already been obtained.

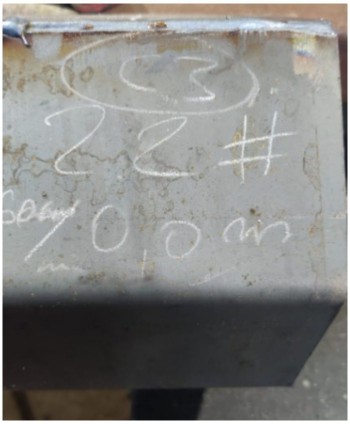


Fig. 4.1. Results of approval experiments, sample welding.

In the experiments of the research, the Fronius® 500i power source and the Fronius® FlexTrack 45 Pro welding tractor were used to ensure the welding processes. Shielding gases M18 and C3 have been used in the experiments so far. Of these, M18 shielding gas was the first to be abandoned, both by modeling and practical results, due to spatter and insufficient penetration (too narrow weld pool).

Laser welding as well as hybrid welding research could be set as one of the future research goals. Being an interesting type of this welding, it has already beendiscussed in the literature review of the previous study [36], [37]; however, the available materials and the unavailability of equipment prevent such a study. Today, the availability of equipment has significantly improved and, accordingly, the possibility of research is higher.

MAIN RESULTS AND CONCLUSIONS

1. The effect on spatter formation when welding with shielding gases M18 and M25 is still observed in the spray-arc material transfer modes. Despite the high plasma temperature in the welding arc, the high CO_2 content still supports the potential for short-circuit formation during the welding process, resulting in droplets forming in the welding bath, which can be seen as a spatter on the surface of the material. When welding with M8 and C3 mixtures, no spatters occur, as the argon content is at least 90 %, ensuring less CO_2 impact on the welding process and the formation of short circuits.

2. Deeper penetration was achieved in all samples welded with M18 and M25 shielding gases. This is possible due to the above-mentioned characteristics of short-circuit formation due to the higher CO_2 content of the shielding gas. It is possible that by reducing the wire feed rate, and thus the welding current, the amount of spatter would be reduced if it were also possible to insure the smooth flow of the molten electrode wire into the bath by reducing the welding speed. As a result, the potential of increasing the heat input to the weld becomes more eventual. It can lead to an increase of both the deformation and the amounts decrease of alloyed elements and the mechanical properties of the weld.

3. In samples welded with M8 and M18 shielding gases, fewer inclusions are observed in the welds. This is due to the fact that the O_2 content that takes part in the weld is lower than for other shielding gases. For this reason, less oxides and other gaseous compounds are formed, which are unable to escape from the liquid phase of the weld.

4. The Mn content was higher in the welds of the samples made with M8 mixture at higher parameters (320 A). Nevertheless, the hardness measurements did not reach the highest values. This can be explained by the uneven microstructure of the joint, as well as the reduced Ni content at higher parameters.

5. Smaller and relatively stable changes in Mn content were observed in welded samples with M25 mixture. However, the hardness test results were not observed to be higher than in the other welded samples.

6. The lowest amount of Mn as an alloying material was observed in all samples welded with C3 mixture. This can be explained by the presence of O_2 in the welding process, as a result of which the alloying elements in the seam are actively burned out. On the other hand, the presence of O_2 in the shielding gas does not significantly affect the changes in the Ni content, and as the current increases, its composition in the joint increases. However, this phenomenon does not ensure the hardness of the weld material, which decreases with increasing welding parameters. Therefore, the use of C3 alloy is not recommended for welding high strength steels at high welding parameters.

7. All samples made with M8 mixture achieved higher hardness values against other shielding gases at the same welding parameters. Sample 280A achieved the highest hardness value among all samples welded in spray-arc transfer modes. Although losses of Mn were observed at lower parameters, no decrease in Ni content was observed in the samples welded with M8 mixtures. This explains the relatively stable hardness values in welded joints.

8. The best combination of weld shape, penetration and hardness parameters was achieved with M8 mixture at 280 A welding parameters. Thus, the previously established hypothesis that welding results in a shielding gas environment at spray-arc transfer parameters for high-strength structural steels is achieved with a shielding gas with a lower percentage of CO_2.

9. A mathematical model was generated and validated to calculate the predicted hardness of weld metal.

10. The hardness of the weld metal in HAZ was achieved lower than the base material for all samples that were welded. It means that the influence of high welding parameters on non-melted welding pool metal is high and decreases its mechanical properties. Therefore, it might not be recommended to use spray-arc in welding of low alloyed high-strength steel or not to over increase these parameters during the welding process.

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