RESEARCHES REGARDING THE QUALITY IMPROVEMENTS FOR METAL WELDED ASSEMBLIES

Doctoral Thesis – Abstract

for obtaining the scientific title of Doctor at
Politehnica University of Timișoara
in the field of doctoral studies Materials Engineering

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PREFACE

Welded joints play a crucial role in the sustainability of our society, being present from the level of microprocessors to major infrastructure projects. At a global level, the share of welded products in the total steel production has already surpassed 45%, which indicates the growing dynamics of this sector. In addition to volumetric growth, a significant emphasis is placed on improving the quality and durability of these joints.

The research conducted as part of the doctoral thesis was focused on the implementation of new technologies in the welding workshop, as well as the development of new products that meet the requirements of customers in the Timișoara area.

The topic of the thesis was chosen based on 10 years of experience as an international welding engineer, with technical responsibility for welding, certified by ISCIR, and participation in various projects in the field of metal fabrication. New machinery has been purchased, on which dozens of preliminary tests were conducted before the industrial-scale adoption of the solutions presented in this thesis.

The doctoral thesis presents the experimental research and results obtained in the joining of dissimilar metals and in improving the quality of welded joints through microalloying. Research and experiments have also been extended to non-ferrous metals such as aluminum and its alloys based on requests from clients of the companies that supported me in my production activities.

Experimental research in the laboratory phase was conducted within the laboratories of the Faculty of Engineering in Hunedoara, the Faculty of Mechanics in Timișoara, the Politehnica University of Timișoara, and the ISIM research institute in Timișoara, while the practical implementation of the subassemblies took place in companies in Hunedoara and Timișoara.

The doctoral thesis was completed under the guidance of Professor Dr. Eng. Heput Teodor, to whom I would like to express my gratitude for the support provided throughout my doctoral studies. I thank the advisory committee for the assistance provided during the experiments conducted, the processing of the obtained data, and the finalization of the doctoral thesis. The suggestions and discussions held with the members of the advisory committee, as well as with the members of the Department of Engineering and Management, have led to the continuous improvement of the thesis as well as the development of scientific articles.

I would also like to thank Professor Dr. Eng. Socalici Ana Virginia for the support provided, the advice given, and for sharing her teaching and professional knowledge. I would like to express my gratitude to the researchers at the National University of Science and Technology POLITEHNICA Bucharest for their support in analyzing the experimental samples, and to Mr. Associate Professor Dr. Eng. Birtok Băneasă Corneliu for his assistance during the International Invention Exhibitions.

Last but not least, I would like to express my gratitude to the management of the

Politehnica University of Timișoara, the Faculty of Engineering in Hunedoara, and the Department of Engineering and Management, for providing a conducive environment throughout the entire process of writing my doctoral thesis.

I would like to especially thank my family for their unconditional support!

CHAPTER 1

PLAN FOR CARRYING OUT EXPERIMENTS AND RESEARCH

In the machine building industry, welded joints account for over 45% of the total amount of steel used. Of this percentage, 80% are quality welded joints executed primarily through robotic means. Continuous research in this field is necessary for improving welding technologies and enhancing the quality of welded joints. Research should be focused on the entire production chain, from the development of quality steels, their processing through laser cutting or mechanical machining, their welding, to post-weld heat treatments.

The fundamental objective of the doctoral thesis is to identify welding solutions for dissimilar materials, to study the microalloying elements that influence weldability, and to develop solutions for cutting and welding aluminum using pulsed laser sources and new gas mixtures.

To achieve the fundamental objective, specific objectives have been established:

- Analyze the current state of welding sources;
- Extending the welding domains of sources by creating experimental robotic tandem welding systems;
- Conducting experiments using pulsed welding sources to improve the shape factor and appearance of the weld bead;
- Researching and experimenting with the effects of microalgae on the weld seam, creating samples, and testing them in the laboratory;
- The realization of joints between dissimilar steels, medium alloy carbon steel with austenitic stainless steel;
- Conducting microscopic, SEM, and spectrographic analyses of the weld seam in dissimilar joints;
- The production of welded parts between dissimilar steels and their testing in an industrial setting;
- Extending research at the request of clients to non-ferrous metals (aluminum and its alloys), developing new protective gases, optimizing pulsed laser cutting;
- Industrial verification of the results obtained during laboratory experiments;
- Formulating conclusions and original contributions, as well as identifying future research directions related to the addressed topic.

Part I - ANALYSIS OF THE CURRENT STATE OF WELDING TECHNOLOGIES FOR METALLIC MATERIALS includes two chapters that analyze the current state of steel welding technologies and the future development trends in the field of welding in a protective gas environment.

Chapter 2 – The study from the specialized literature on the welding of metallic materials presents the current state of the welding process worldwide, an overview of the gas shielded welding procedure, the types of metal transfer from the electrode to the workpiece, and the influence of electrical and technological parameters on the quality of the welded joint.

Chapter 3 - The study on the evolution of welding equipment presents the latest technologies and sources of pulsed current welding, the development of robotic tandem welding systems to enhance the quality and productivity of the welding process.

Part II - RESEARCH AND EXPERIMENTATION ON WELDED METAL JOINTS, includes four chapters and presents the author's own research conducted in both laboratory and production phases regarding the identification of solutions for joining dissimilar materials, cutting, and welding non-ferrous materials using laser technology.

Chapter 4 - Experimental research on the joining of steels from different groups presents a project for the joining of medium alloy carbon steel with an austenitic stainless steel. The innovation consisted of designing a stainless steel cover to protect the piston in the extrusion machine, aimed at preventing corrosion of the piston when in contact with aluminum at high temperatures and pressures. The welding technology was developed by the company Hydromatic System Timisoara.

Chapter 5 - Experimental Research on the Strengthening of Welded Joints of HSLA Steels presents a method for improving a mechanical parameter (impact resistance) through the microalloying of the weld bead. The practical application is in the welding of box beams subjected to operational shocks, such as the arms of an excavator. In the production workshop, tests were conducted using welding wires with different compositions, and samples were created that were tested in the laboratory of the Faculty of Mechanics at UPT. The influence of nickel on impact resistance (resilience) has been determined, and industrial production has commenced following the validation of laboratory tests.

Chapter 6 - Data Processing and Analysis of the Results Obtained presents the actual research conducted within the ISIM Timisoara laboratory. Procedures for sample collection have been developed, and analysis zones (lines) have been established to focus research efforts in the relevant areas of the weld seam. Analyses were conducted using an optical microscope at magnifications of up to 1000x, high-precision spectrometric analyses with the OE750 spectrometer, and analyses with an electron microscope equipped with EDX of the Tescan VEGALMU type. The results obtained lead to the improvement of the welding process, to the optimal determination of the preheating temperature, to the optimal selection of the welding wire, and to the identification of defects in order to avoid them later on.

Chapter 7 – The extension of experimental results on the thermal processing of non-ferrous alloys presents the industrial experiments conducted regarding the cutting quality of aluminum sheet parts intended for welding. Experiments have been conducted using pulsed laser technology, and new mixtures of active gases for aluminum cutting have been developed in collaboration with the company LINDE. The obtained data were analyzed using 3D graphical methods in Mathlab. The results have been validated industrially and have made it possible to increase the cutting thickness by 33% while simultaneously reducing the power consumed by 15%.

Chapter 8 – Final Conclusions. Original contributions. Future research directions present the final conclusions obtained, the original contributions, the way of implementing the research results in practice, as well as the directions for continuing the research.

In the final section, the bibliographic sources, dissemination of research results, and appendices are presented.

PART I – ANALYSIS OF THE CURRENT STATE OF WELDING TECHNOLOGIES FOR METAL MATERIALS

CHAPTER 2
STUDY FROM THE SPECIALIZED LITERATURE ON WELDING OF METALLIC MATERIALS

Depending on the energy input, welding processes are classified into:

- thermoelectric welding, where the energy source is an electric arc;
- thermochemical welding, where the energy source is a flame or thermite;
- radiative welding, where the energy source can be an electron beam or a laser

beam;

- mechanized welding, where all basic operations are performed with the help of welding robots.

In Fig. 1/2.2, the classification of welding processes is presented [1/5].

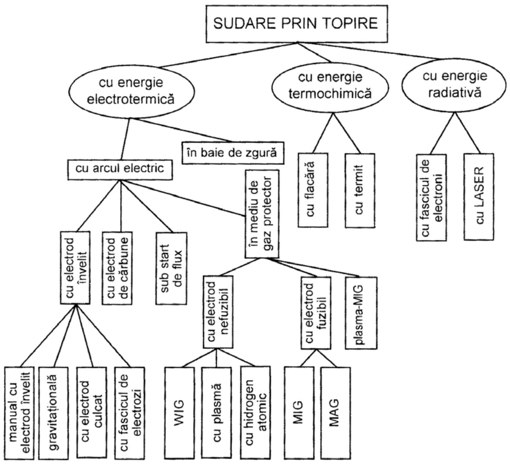

Fig. 1/2.2 Classification of welding processes

Depending on the method of execution, welding is classified into:

- Manual welding, where all operations are performed manually;
- Semi-automatic welding, where part of the operations is performed automatically (for example, the movement of the welding gun or the feeding of filler material is done automatically);
- automatic welding, where all operations are performed automatically (in the case of robotic welding cells).

The symbols for welding processes are standardized according to ISO 4063 [1/5] and are used in execution drawings.

In addition to the symbols that indicate the type of welding process, the standard also refers to the geometric parameters of the weld such as [2/6], [3/7]:

- tip cord, linear or circular;
- cord length;
- shape of the welding joint;
- the thickness of the base material;
- type of joint (e.g., end-to-end or corner).

Table 1/2.1 presents the symbols for fusion welding processes, ISO 4063.

Table 1/2.1 Symbols of fusion welding processes

Proces de sudare	Simbol	Nr. conform ISO 4063	Nr. de ordine
Sudarea cu gaze	G	3	4.6.2.3.02
Sudarea $C_2H_2 - O_2$	G	311	-
Sudarea cu arc electric	-	11	-
Sudarea manuală cu arc electric	E	111	4.6.2.4.08
Sudarea cu arc electric cu electrozi tubulari (autoprotectori)	MF	114	4.6.2.4.14
Sudarea sub strat de flux	UP	12	4.6.2.4.22
Sudarea cu gaz protector	SG	-	-
Sudarea metal + gaz de protecție	MSG	13	-
MAG	MAG	135	-
MAG cu sârmă tubulară	MAG	136	-
MIG	MIG	131	4.6.2.4.34
WIG	WIG	141	4.6.2.4.42
W + plasmă	WP	15	-
Sudarea cu fascicul laser	LA	751	4.6.2.5.04
Sudarea fascicol electroni	EB	76	4.6.2.5.08
Sudarea bolțurilor cu arc electric	B	781	-

The most commonly used procedure is the semi-automatic variant (the wire electrode feed speed is automatically correlated with the welding current), while the gun feed speed is manual [4/10], [5/11].

CHAPTER 3

STUDY ON THE EVOLUTION OF WELDING EQUIPMENT

For the study of the effects of electrical and technological parameters that influence the welding process, a linear welding robot has been constructed (Fig 2/3.8). The role of this robot is to ensure welding speeds that can be measured and digitally adjusted, thus eliminating the effects of manual welding where the welding speed cannot be controlled and measured.

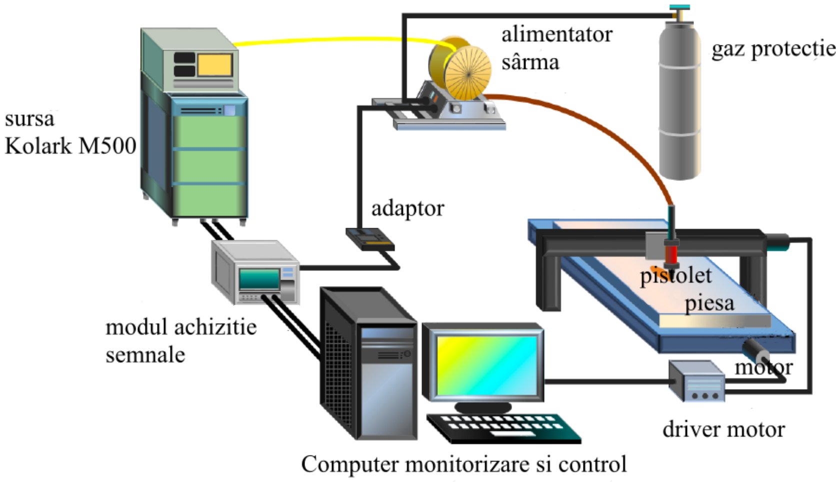

Fig. 2/3.8 Schematic of the experimental welding installation

The next components have been used:

- Kolark M500 welding power source;
- The automatic wire feeder;
- The USB-205 MULTIFUNCTION analog signal acquisition module, equipped with 8 channels used for reading the electric arc voltage Ua, the average welding current IM, and the wire feed speed vss measured in cm/min;
- WEIHONG 1300 CNC router, where the welding gun was mounted on the crossbeam. The travel speeds of the traverse can be controlled through the monitoring-control computer, and in this case, the welding speeds are compared to the actual measured speeds in cm/min.

The increase in productivity and automation necessitates a rise in welding speed, which is technologically limited by the wire feed unit. The solution in this case is to increase the number of welding wires that converge simultaneously in the molten pool.

From the perspective of the formation of the metal bath, the most common situation is when the two wires converge in the same metal bath. In practice, especially in multi-layer welding, there is also the possibility of sufficiently spacing the two wires so that each can independently form its own molten metal pool.

From a construction standpoint, tandem welding guns are built with a special gas nozzle that has an oval shape. Since it needs to dissipate a large amount of heat, the nozzle is made of copper and has water cooling. Inside, there are the two contact nozzles that ensure the transmission of current to the welding wires. The welding wires are ordered in a master-slave configuration, with the first wire in the welding direction always being the "master" wire.

To achieve quality welds, the tandem gun must have both guiding tubes constructed rigidly. Additional cooling is also a requirement, especially since the operating regime of these guns is continuous. The electrical insulation between the two welding wires is a very important factor, preventing direct discharges between the wires and blocking the welding process.

Within the metalworking workshop, experiments were conducted on standard and tandem sources in the construction of beams for cranes. The welding at the edge of the S355J2 plate with a thickness of 20mm resulted in:

• Layers with a height of 6-7mm for both sources;

• Welding speed of 30 cm/min, wire feed speed of 13.5 m/min at the standard source;

• Welding speed of 80 cm/min, wire feed speed 19.5 m/min at the master source and 9 m/min at the slave source;

• High deposition rates of over 15 kg/h in tandem welding;

• The number of passes reduced from 15 to 10 in the case of tandem welding;

• 20% higher productivity;

In the last decade, the tandem welding system has developed significantly, with effects on:

• Increased productivity through a higher deposition rate and the integration of the welding gun into robotic installations;

• Improving quality by using combinations of wires with different compositions and different electrical regimes.

Another field that is continuously developing is that of tubular wires. The composition of the flows of these wires ensures the deoxidation of the metal bath through the content of Al and Si, as well as the reduction of hydrogen content through the fluorides MnF_3, CaF_2, Na_2SiF_6, K_2SiF_6, Na_3AlF_6, and Li_3AlF_6, which can be recovered from steelmaking slags [6/40]. The tube wire format ensures the protection of the metal bath after welding and prevents dripping during vertical welding. The quality of the welded joint using tubular wires recommends their use for welding high-strength HSLA steels.

PART II
RESEARCH AND EXPERIMENTATION ON WELDED METAL JOINTS

CHAPTER 4
EXPERIMENTAL RESEARCH ON THE JOINING OF STEELS FROM DIFFERENT GROUPS

The weld between stainless steel and high-strength carbon steel is commonly used in the automotive industry. For this purpose, a method for the protection and extension of the lifespan of pistons in aluminum-magnesium alloy extrusion presses has been researched and implemented. [7/41]. In the technological process of extrusion, the aluminum-magnesium alloy (AlSiMg11) standard is pushed by the piston inside the extrusion cylinder (Fig. 3/4.4.) [8/42].

The most mechanically stressed element, both dynamically and statically, is the piston, which during operation reaches temperatures of up to 400 °C and pressures of 300-700 MPa.

This must have exceptional and sometimes complementary qualities:

• Bending resistance – buckling of the rod, especially in a retracted position;

• Working at high temperatures;

• Resistance to chemical corrosion upon contact with magnesium, which is highly reactive to the carbon in the composition of steel.

For this purpose, a prototype rod was practically created using superior mechanical materials and a special method of joining them. The body of the rod has been improved by choosing a stronger steel with a medium carbon content. The end of the rod was made by turning from austenitic stainless steel. The body and the head of the rod were assembled through welding, a technology developed in the welding workshop of the company SC Hydromatic Timișoara.

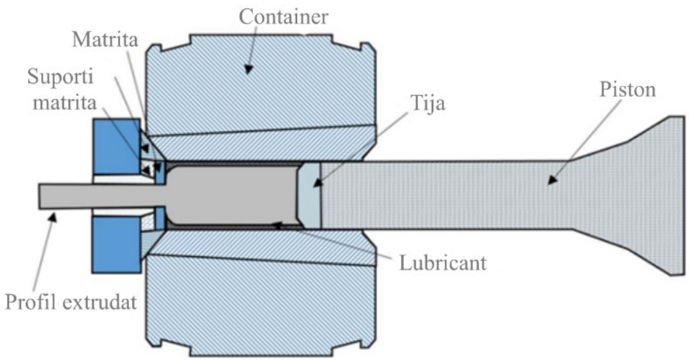

Fig. 3/4.4 Typical application of the extrusion process

The stainless steel used at the head of the rod was tested for corrosion by being in contact with the AlSiMg11 alloy for 24 hours at a temperature of 400°C in the stress relief heat treatment oven. Based on the results obtained from these experiments, the type of stainless steel AISI304 was chosen.

The welding procedure and welding parameters were tested to achieve a weld that would create a gradual transition between the high carbon content of the rod and the carbon-free stainless steel. It was also aimed at achieving a structure as resilient as possible.

In this case, the control of this transition zone was achieved through experimentation and the selection of an optimal welding wire that ensures both the necessary mechanical strength and resistance to corrosion and temperature. The element of interest in the alloy matrix in this case is nickel, considering that the joint area from a metallurgical standpoint is closer to stainless steel than to carbon steel.

Dissimilar joints require technologies that are far superior to those for joining similar metals and alloys, and they are usually avoided from the design phase onward. However, there are increasingly numerous cases that require the design of such joints from the outset in situations where the joint needs different properties from the two pieces, and if the material of one of the pieces is very expensive, the quantity of that material is reduced at the expense of the other material (for example, in the case of cladding).

In cases where dissimilar jointing is not possible through conventional welding processes, it can still be achieved through the following methods:

- The introduction of a third alloy in the weld seam that is compatible with both materials used. An example is nickel in carbon steel – stainless steel joints (the case studied earlier), similarly for cast iron – carbon steel joints or copper – aluminum joints:
- The joining using a layer of a third alloy between the initial alloys that are to be joined;
- The use of special laser technologies.

CHAPTER 5
EXPERIMENTAL RESEARCH ON INCREASING THE STRENGTH OF WELDED JOINTS OF MICROALLOYED HSLA STEELS

The development of new types of consumables for welding HSLA steels represents a challenge for the machine-building industry, considering the wide variety of consumables (MIG-MAG welding wires) and their diverse content in new alloying elements. For the analysis, structural examinations were conducted under a microscope and tests were performed on the Charpy impact testing machine. The welded material was HSLA steel with a thickness of 10mm.

The aim of the research in this chapter is to increase the impact resistance of the weld seam through microalloying using alloyed welding wires at values equal to or higher than that of the base material [11/60]. The element studied in these tests is nickel, and its composition in welding wires can vary between 0 and 9.5%. The main advantage of nickel is that through microalloying and dilution in the metal bath, it can increase impact resistance as well as its temperature range, including in the realm of negative temperatures. Another advantage of nickel is that it does not form carbides that weaken the weld and can be dissolved in large proportions in austenite and ferrite. The filler materials (1.2mm diameter welding wires) have been selected from a wide range to cover an element for which the study was conducted, namely nickel. Thus, wires were selected from the ER70 brand without nickel to the ER308 brand, which contains 9.5% nickel [12/59]. The welding tests were carried out on 10mm thick plate samples measuring 50x100mm that were welded together. The pre-welding preparation of the joints was done on the CNC milling machine in order to achieve a weld joint in an "X" shape. The chosen welding procedure is "active metal gas" (MAG). The impact tests were conducted in the laboratory of the Faculty of Mechanics at UPT. The tests were conducted on batches of 5 test tubes for the 4 types of additive materials.

In the picture. 4/5.6-7/5.9 is presented the aspect of the sample break after testing for the filler materials ER70, ER100, ER120, ER308:

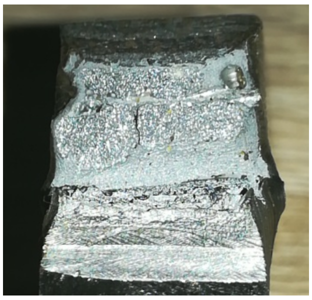

Fig. 4/5.6 Aspect of the sample welded with ER70

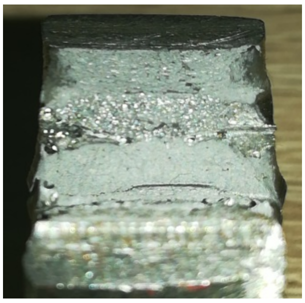

Fig. 5/5.7 6 Aspect of the sample welded with ER100

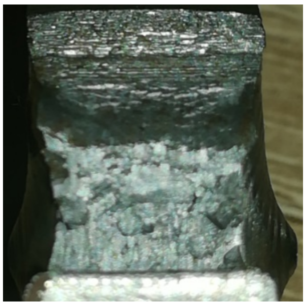

Fig. 6/5.8 6 Aspect of the sample welded with ER120

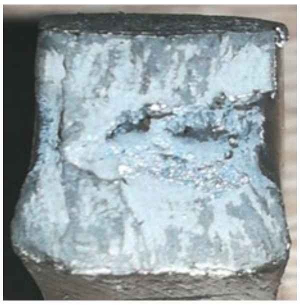

Fig. 7/5.9 6 Aspect of the sample welded with ER308

The best results were obtained with nickel concentrations of 2 - 3% in the welding wire, which corresponds to 1.6% in the weld bead after dilution using the filler material ER120 [11/60]. The appearance of the grains in the fracture plane generally shows a fine structure; all samples withstood the impact test without breaking, which indicates good resilience of the welds.

The increase in nickel content in the ER308 filler material shows a decrease in impact resistance, the cause being the large austenitic grains visible in the fracture section.

CHAPTER 6
DATA PROCESSING AND ANALYSIS OF OBTAINED RESULTS

For the execution of the welding tests, an important requirement was the experimentation and testing of the electrical and technological process parameters, so that the weld bead has dimensions H and L, with the optimal aspect ratio H/L required by the dimensions and geometry of the samples. The experiments were based on the welding regimes imposed by the welding technical specifications (WPS) for MAG welding of S355J2 steel plates edge to edge [13/57].

The hardness analyses, as well as macroscopic, microscopic optical and electronic, and X-ray spectrographic analyses, were carried out at the National Institute for Research and Development in Welding and Material Testing ISIM Timișoara.

In figure 8/6.5, the sample is presented, with yellow lines delineating the three areas that result after welding:

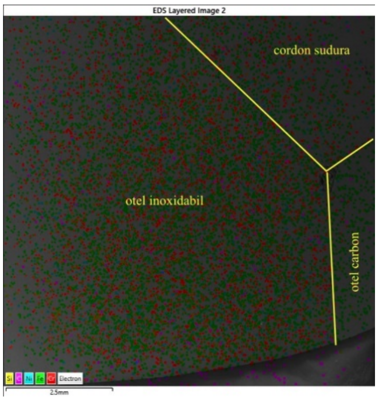

Fig. 8/6.5 Overview of the test in EDS technology

With the help of this analysis, the degree of dilution of the materials in the weld bead can be measured. Thus, the most relevant element for measuring the degree of dilution is chromium, marked in red in Fig 6.5. In the quality certificates, we have a chromium concentration of 19.1% for stainless steel and a concentration of 0.85% for carbon steel. After scaling the EDS system with these 2 values, the concentration of chromium in the weld seam results in 11%, a value that confirms the data presented in chapter 4. Figure 9/6.6 presents each element in detail. It is observed that nickel can also be read and considered as an indicator of the degree of dilution of materials in the weld bead.

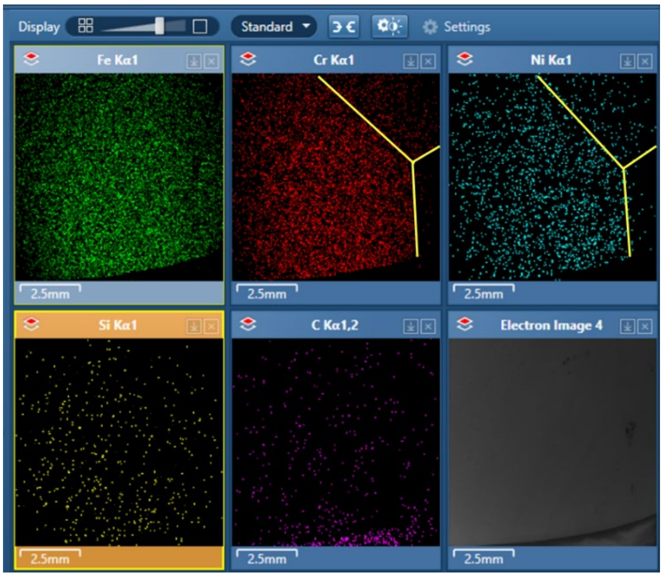

Fig. 9/6.6 Overview of the EDS technology test detailed by elements.

For the detailed study of the weld seam and the heat-affected zone (HAZ), three scanning lines were chosen using the electron microscope. Thus, for the welding cord, lines 14 and 16 were defined; for carbon steel HAZ, lines 12 and 18; for stainless steel HAZ, lines 11 and 15. As a way of mixing the chemical elements, in lines 14 and 16 we can consider that the mixture of Fe with Cr, Ni is made by melting in the liquid phase thus by dilution. In the thermally affected areas, lines 11, 12, 15, and 18, we can consider that the transfer of elements from the weld seam occurs solely through diffusion.

Figure 10/6.7 shows the arrangement of the scanning lines on the sample.

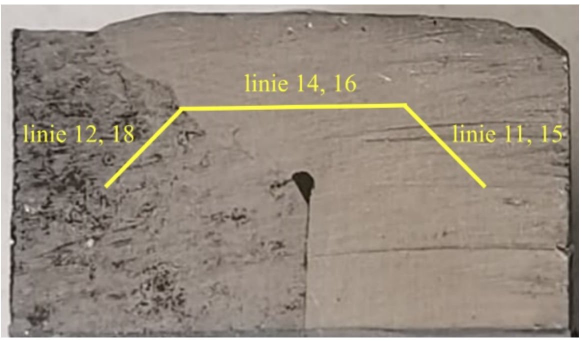

Fig. 10/6.7 The arrangement of scanning lines on the weld sample.

Lines 12 and 18 correspond to the alloyed carbon steel 34CrNiMo6, while lines 11 and 15 correspond to the stainless steel AISI 304. Lines 14 and 16 correspond to the two wires used for welding, ER309 and ER309. For lines 14 and 16, the electronic scanning of Fe and Cr atoms shows a constant distribution of their concentrations along the scanning line. This fact indicates a good homogenization of these elements through dilution in the liquid metal bath (Fig. 11/6.8). From the spectral analysis, if we consider chromium as a reference element, we observe its dilution from values of 20% corresponding to the welded AISI304 steel to values of 16% in the vicinity of the fusion line.

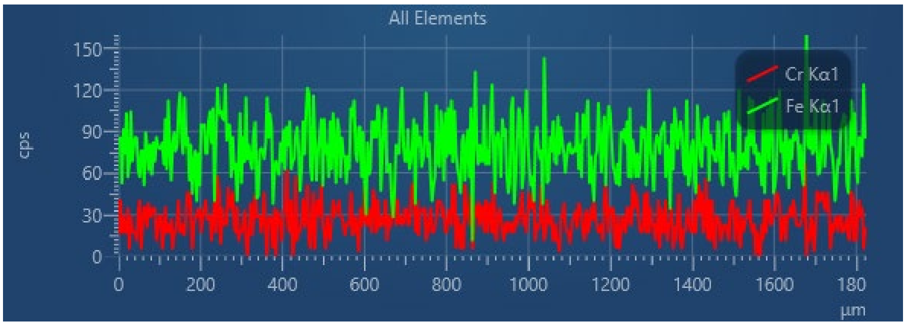

Fig. 11/6.8 Distribution of iron and chromium atoms in the weld seam.

To highlight the fusion line between the two austenitic stainless steels, the following was analyzed under the optical microscope:

- The welding filler metal becomes an alloy of 70% ER309 and 30% AISI304. During the transition from the liquid phase to the solid phase, primary ferrite grains appear, which over time grow and form globular ferrite in grains that are visibly larger than the other ferritic formations. The identification of these grains is an indication that they are located in the weld zone where the steel has undergone a phase change;
- The thermally affected zone does not change phase, but recrystallization and finishing of the ferrite occurs with the appearance of lamellar ferrite;
- The fusion line shows a complete dilution between the two austenitic steels, and unlike the fusion line with carbon steel, it does not exhibit dendritic formations between the two steels.

Microscopic examination can indicate the ferrite content (Fig. 12/6.16) and shows the types of new ferritic formations that have appeared in the weld bead (e.g. globular ferrite and fine lamellar ferrite).

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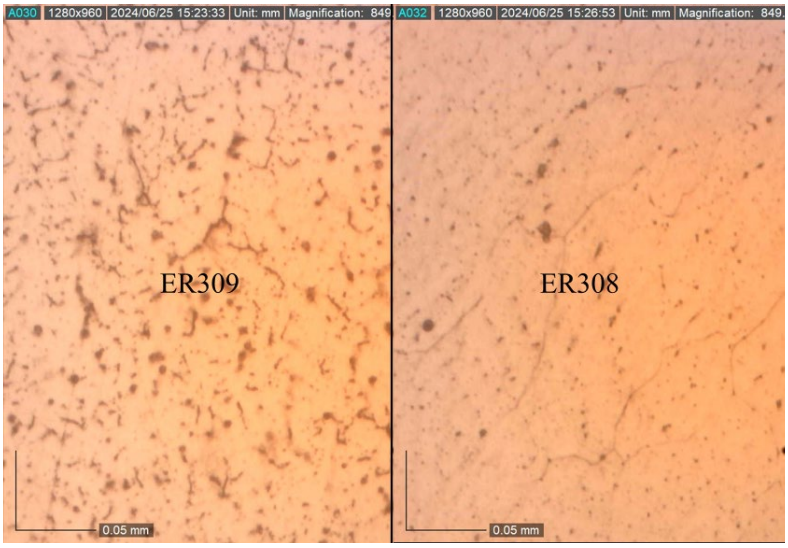

Fig12/6.16 Comparison of the content of welding filler ER309-ER308.

In addition to the importance of ferrite content in the welding seam, a new factor indicated by microscopic examination is the dendritic formation rate in the fusion line with carbon steel. This depends on the linear energy and preheating temperature, as well as on the post-welding treatments of slow cooling.

CHAPTER 7
EXTENSION OF EXPERIMENTAL RESULTS TO THE THERMAL PROCESSING OF NON-FERROUS ALLOYS

In order to improve the cutting domain, specifically the increase in material thickness and cutting speed, the following were experimented with:

- Changing the protective gas from nitrogen (inert) to oxygen (active);
- The use of a new mode in the field of laser sources, namely the pulsed mode.

The cutting tests conducted were performed using the entire frequency spectrum of the laser source, grouped into low, medium, and high frequencies [14/69]:

At low frequencies, 50 Hz, alumina is fragmented into relatively large pieces on the order of 200 microns, which still retain the insulating effect of the molten aluminum from the laser beam, making energy transfer to the melt and cutting difficult.

At medium frequencies, 3000 Hz, alumina is fragmented into pieces on the order of 20 microns, which are easily removed by the oxygen jet.

At high frequencies of 40,000 Hz, alumina is fragmented into very fine parts that are incorporated into the molten aluminum.

For the experiments, 4 special gas compositions were created, in which the parameter was the concentration of oxygen. The four types of gas had 25%, 50%, 75%, and 100% oxygen [15/70]. For the macroscopic evaluation of cut quality, a special cutting program was designed to cut 10 test lines, with a parameter gradually modified in 10 steps. The parameters that most influence the quality of the cut are the laser power and the cutting speed. These parameters were analyzed independently, and in the end, a three-dimensional analysis of the cutting quality was performed based on the laser power and cutting speed for the four tested gas compositions.

Results obtained:

- Changing the shielding gas from nitrogen to oxygen leads to a 50% increase in cutting thicknesses;
- The use of the laser in a pulsed manner leads to a reduction in the width of the cut and its roughness;
- The pulse frequency is an essential parameter regarding the removal of alumina. The best results are achieved at medium frequencies of 3000Hz when the resulting burr is minimal and the roughness is acceptable.
- The operation of the oxygen laser is more stable than that of the nitrogen laser, and gas consumption decreases by 68%.
- The total operating cost decreases by 30% due to the reduction in the gas flow required, as well as the lower price of oxygen compared to nitrogen.

From the study of the effects of cutting gas, it is observed that for a sheet of 1 mm thickness, a cutting speed of 50 mm/s and a laser power of 900W, it is possible to cut it using both oxygen and nitrogen. The cutting gas pressure plays an important role in achieving clean cuts without burrs. The mechanism for removing molten aluminum is done differently for the two gases. In the case of nitrogen, being inert, the removal of molten aluminum is done exclusively based on its kinetic energy. From experiments, an optimal pressure range of 17 - 19 bar is observed. In the case of higher pressure, there is an additional cooling effect on the cut, a significant increase in nitrogen consumption, and an increase in the cutting power of the laser. In the case of lower pressure, the formation of burrs is observed at the bottom of the cut, and even the non-penetration of the sheet at pressures below 10 bar. In the case of oxygen, molten aluminum is removed through two effects: the kinetic energy of the oxygen and the expansion effect of aluminum during its transformation into alumina.

CHAPTER 8
FINAL CONCLUSIONS. ORIGINAL CONTRIBUTIONS
FUTURE RESEARCH DIRECTIONS

Final conclusions

Analyzing the specialized literature and the results of my own experimental research regarding the welding of ferrous and non-ferrous metal materials, the following conclusions emerge:

The technological development of power electronics and welding sources paves the way for new welding technologies, leading to the emergence of new technological parameters that, through optimization, result in a qualitative improvement of welded joints.

- Increasing productivity involves the development of new technical solutions regarding the welding process, such as tandem welding with two wires and tubular wire welding.
- Development of technologies for the preparation of metallic materials (cutting) for welding purposes. Laser deburring in pulsed mode.

In the western region of Romania, there is a marked development of the automotive industry, where the demand for special welded joints is on the rise. The experiments that formed the basis of this doctoral thesis were conducted in Timișoara, based on the requests of some important clients for special welded joints. Thus, piston rods for aluminum extrusion were produced and delivered to companies such as TRW, and welded joints made of stainless steel were supplied to companies like Continental, Mahle, etc.

Welding technologies and joint design have been developed within the design workshops of the companies Hidromaticsystem SRL and Romadoor SRL. At the request of clients, the cutting and welding workshop for non-ferrous metals, especially aluminum and its alloys, has been developed. CO2 and pulsed fiber cutting lasers have been purchased, and new cutting technologies for aluminum sheets intended for welding have been developed. The primary focus was on the quality and appearance of the cut and welded products, followed by increasing productivity and reducing production costs.

Research conducted in the field of dissimilar metal joints through welding leads to the possibility of creating parts and subassemblies with higher durability. These studies are being continued by expanding the range of welded metals, moving from welding stainless steel with carbon steel to welding copper with aluminum using laser technology.

In the field of welding in a protective gas environment, experiments and research have been conducted to enhance the productivity and quality of welded joints. Thus, modern synergic double-pulsed sources of 500 amperes, type Kolark M500, were purchased for the welding workshop. With the help of these parallel sources, along with the command and control unit designed and built in-house, a tandem linear welding robot was developed, intended for the automatic creation of long welds required in the production of crane beams. Research has been conducted in the field of laser cutting for both steel and aluminum to enhance productivity and quality. In collaboration with the company Linde SRL, new solutions for cutting aluminum have been found using active gases such as oxygen and its combinations with nitrogen, particularly applicable in the field of high-quality aluminum plate cutting.

Original contributions

Both original contributions developed in the laboratory and industrial phases can be considered:

- determining the influence of the electrical parameters of the welding source and the technological parameters of the welding process on the geometric shape of the weld bead;
- determining the influence of the welding source (standard and tandem) on the deposition rate and linear energy, with an effect on increasing productivity and quality;

- establishing the welding technology for joining steels from different groups, specifically austenitic stainless steels with high-strength medium-alloy carbon steel;
- the practical realization of the piston used in the extrusion of aluminum and magnesium;
- establishing the welding technology for joining high-strength low-alloy (HSLA) steels to enhance impact resistance through micro-alloying of the weld bead;
- the practical implementation of the joining of HSLA steels with the achievement of impact resistance of the weld bead superior to that of the base material;
- analysis of the weld seam using spectrograph, macro and microscopic analyses, analysis of alloying elements with an electron microscope;
- the development and implementation on the standard laser of aluminum cutting technology using oxygen and frequency modulation of the laser beam;
- implementation of the automatic oxygen-nitrogen mixing system based on the composition of the processed aluminum plates;
- research on optimizing cutting parameters to enhance cutting quality, with positive effects on welding;
- practical experiments for laser pulsed cutting of aluminum, increasing the thickness of the cut sheet by reducing the power of the laser source.

In the course of research and experiments in the laboratory phase, collaboration was established with UPT Faculty of Mechanics for mechanical testing and with ISIM Timișoara for optical microscopy, electron microscopy, and spectrometry.

The laboratory analyses yielded the following results:

- the optimal chemical compositions of the filler elements (welding wires) in order to achieve weld bead strength values equal to or greater than those of the joined metals;
- the optimal aspects of fusion lines to ensure the highest possible mechanical strength of the welded joints;
- highlighting the defects that may occur in the weld seam and the possibilities for remedying them by adjusting the welding technological parameters.

Within the production workshops of the executing companies, trials and experiments were conducted regarding the geometry of the weld bead by optimizing:

- the electrical parameters of the pulsed current sources;
- the technological parameters of the welding process.

Based on these, welding procedures (WPS) have been validated and approved for both the root layers and the fill layers of the weld bead.

Within the production workshops of Linde SRL, experimental mixtures of oxygen and nitrogen were created, leading to the validation and approval of new methods for cutting aluminum sheets using pulsed laser technology.

Future research directions

Based on the research conducted, the results obtained, and the existing facilities, I believe that further research can be developed in the following directions:

- the combination of dissimilar metals, for example, copper and aluminum, used in the electric vehicle industry;
- the combination of high-strength steels to increase the impact resistance of the joint and to expand their temperature usage range;
- the development of tandem welding systems, increasing the number of wires introduced simultaneously into the molten bath;
- the development of new gas mixtures used in the cutting and welding processes of metals.

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