Analysis and prediction of welding deformations of ship panels in prefabrication process.

Huggo Sena Batista

Master Thesis

presented in partial fulfillment
of the requirements for the double degree:
"Advanced Master in Naval Architecture" conferred by University of Liege
"Master of Sciences in Applied Mechanics, specialization in Hydrodynamics,
Energetics and Propulsion" conferred by Ecole Centrale de Nantes

developed at West Pomeranian University of Technology, Szczecin
in the framework of the

"EMSHIP"
Erasmus Mundus Master Course
in "Integrated Advanced Ship Design"

Ref. 159652-1-2009-1-BE-ERA MUNDUS-EMMC

Supervisor :	PhD Tadeusz Graczyk, West Pomeranian University of Technology, Szczecin
Reviewer:	Dr.-Ing. Ulrich Kothe, University of Rostock

Szczecin, January 2012

ABSTRACT

In the shipbuilding industry problems related to the welding process are very often identified, especially because it must fulfil several requirements as for design as for production, moreover it needs to be performed under strict supervision and also by very skilled workers. Intending to minimize the effects caused by the welding in the shipyards, over the year many works have been developed showing methods to predict and mitigate these effects, mainly through Finite Element Analyses where is possible to verify points of improvement along the welding process, for example in terms of process sequence or welding parameter.

In this current work is proposed a practical way to predict the welding-induced deformation of 5-mm-thick steel ship panels prefabricated in a traditional Polish shipyard through a number of experiments and data collection performed on the butt welding line using Submerged Arc Welding (SAW). For these experiments a Design of Experiment (DoE) has been organized so as to get different condition of welding energy as well as the values of the pressure applied by the devices used during the welding and then different trials and data collection were carefully carried out in the shipyard to realize what are the most important welding parameter which are contributing for the problem (welding deformation). The data available have been analyzed by the statistical software Design-Expert® and considerations about data arrangement have also been done aiming to provide the best condition to describe the welding deformation.

As a result this work provides an approach to predict the welding-induced deformation within the workshop by way of numerical equation where the main welding parameters were taken into account and dully weighted by the software. Some partial evaluations of the accuracy of the equations were achieved and their results considered satisfactory regarding to the comparison between the actual values versus predicted values. Another important issue reached is the data arrangement used to compute the welding deformation and finally this thesis is completed with recommendations and suggestions for the future investigation.

RESUMO

Problemas relacionados ao processo de Soldagem são muito comuns na indústria de construção naval, especialmente pelo fato de ser necessário o atendimento de diversos requisites tanto no que diz respeito à etapa de design quanto ao processo produtivo, além disso, este tipo de processo precisa ser rigorosamente supervisionado e produzido por profissionais capacitados. Com a intenção de reduzir os problemas de solda nos estaleiros, ao longo dos anos muitos trabalhos tem sido desenvolvidos principalmente com o uso de Análise de Elementos Finitos e tem mostrado métodos para prever e mitigar tais efeitos os processos de soldagem, seja na sequência de operações seja nos parâmetros de solda.

No presente trabalho é mostrada uma forma prática de prever a deformação induzida pela solda em painéis de navios de aço com 5 mm espessura pré-fabricados em um tradicional estaleiro polonês, através de uma série de experimentos e coleta de dados realizados na linha de soldagem topo usando soldagem de arco submerso. Para esses experimentos, um desenho experimental foi organizado para conseguir diferentes condições de energia de solda assim como diferentes valores de pressões para os dispositivos usados na soldagem e então, alguns testes e coleta de dados foram cuidadosamente feitos no estaleiro para verificar quais são os principais fatores que estão contribuindo para a ocorrência do problema (deformação). Os dados disponíveis foram analisados pelo software Design-Expert® e considerações sobre a forma de organizar os dados também foi feita com o objetivo de descrever corretamente a deformação.

Como resultado, esse trabalho fornece uma método de prever a deformação induzida pela solda no processo produtivo através de uma equação onde os efeitos dos principais parâmetros de soldagem são devidamente distribuídos pelo software. Algumas avaliações parciais sobre a acurácia dessas equações foram feitas comparando os valores previstos com os valores reais obtidos no estaleiro e os resultados foram considerados satisfatórios. Outro ponto importante alcançado é em relação ao arranjo dos dados usados para calcular a deformação de solda e, finalmente, esta dissertação e concluída com recomendações e sugestões para trabalhos futuros.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION

ANOVA	Analysis of Variance
DoE	Design of Experiment
FEA	Finite Element Analysis
FEM	Finite Element Method
GMAW	Gas Metal Arc Welding
HAZ	Heated Affected Zone
MAG	Metal Active Gas
MIG	Metal Inert Gas
MMA	Manual Metal Arc
SAW	Submerged Arc Welding
SPC	Statistical Process Control
TIG	Tungsten Inert Gas

Declaration of Authorship

I declare that this thesis and the work presented in it are my own and have been generated by me as the result of my own original research.

Where I have consulted the published work of others, this is always clearly attributed.

Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.

I have acknowledged all main sources of help.

Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma.

I cede copyright of the thesis in favor of the West Pomeranian University of Technology, Szczecin.

Date: 16 of January of 2012 Signature: Thiago Serra Batista

1 INTRODUCTION

1.1 Overview

Considering the understanding of ship production nowadays, many issue scan be drawn related to design of ships, capacity of the shipyards, work station, technology of production and these subjects are in constant development due their importance in the costs, schedule and quality of the industry hence improvements in the shipbuilding industry should be constantly done intending to reduce delays, to mitigate the rework or even creating new solutions to produce and like that to increase the competitiveness of the shipyard in the market.

Concerning the naval field and talking about naval construction with its main peculiarities highlighted, is possible to figure out that many characteristics might be improved in order to save money and time.

The following items can be given as examples possible of improvements in the ship production technology:

- Development of technology related to raw material used (new materials applied in the shipbuilding industry);
- Reduction or elimination of rework due to deformations after welding (straightening process) in workshops;
- Reduction of time to prepare cut outs on steel parts;
- Development of technology to adjust welded parts (section assembly);
- Or simply to enhance the work flow of the pieces, plates or panels among the work stations in the workshops as well as the indoor activities in the design office during designing.

Computational simulation might aid the researchers to perform changes in the shipyard without physical changes but sometimes other types of experiments have to be performed intending to check the actual results. However, certain changes or improvement cannot be performed or applied in the shipyard totally per chance or without any preparation. Many times a number of experimental trials must be done before performing such modification.

Some reasons to illustrate this affirmative may be exposed, as described below:

- The time to deliver the ship – which is usually tight and is strongly recommended that is not be disturbed;

- The costs – mainly related to the rework or attributed to delays due to unsuccessful experiment applied in the workshop;
- Or equally important are the factors related to the ship construction by itself – as it is not considered as mass production, might be difficult to rearrange the schedule or adjust needs along the way.

In other words, each ship has her specific issues and demands which must be respected. Hence it is coherent to say that every ship is an odd project. Consequently, each project has particularities which must be taken into account during the ship design phase. Nevertheless, aside from the individuality of each vessel, some stages during the ship construction are frequent and similar to the majority of vessels or watercraft and it might be useful for the practice in shipbuilding. Industrial processes, type of material, or lay out organization are some of the mutual aspects for every type of ship i.e. they do not need to be unique during the ship production neither for every ship.

From this point of view is also easy to verify usual characteristics among the ships, such as: some of them must work in several different sea conditions while the other carry some cargo out or accomplish some similar task during her life and so on.

Looking forward for reducing process time, wasting of material, man power and consequently wasting of money are concentrated the shipyards and design office. For that reason some ideas and experiments in the shipyard have been carried out by the researchers over the years. As samples of this kind of work is easily found in material from Birk-Sørensen (1999) where is shown a methodology to predict the welding distortion and avoid reworks with straightening, for instance. In the same way of thinking is also possible to check the effort made by Awang (2002) where the experiment tries to understand the effects caused by the welding on the structure as well as the undertaking from Törnblom (2007) which assists those effects related between the weld geometries on the mechanical properties of undermatched welds.

Generally, one the most relevant problem in the shipbuilding industry is regarding to the steel welding, as mentioned earlier. This process causes distortion on steel parts due to the residual stress which comes from the combination between the welding parameter together with the geometries of the steel pieces, roughly speaking.

This process is a kind of complex activity to be controlled and needs skilled worker furthermore involving extremely high temperature which generates distortion afterwards, like mentioned by Awang (2002).

However there are many others factors which acting on the welding results apart from the welding parameter and the geometries of the steel piece and some of them have been described and analyzed during this work in order to mitigate the deformation after welding.

Those factors are related to the welding equipment used to perform the butt welding on steel panel with SAW in a traditional Polish Shipyard.

1.2 Scope of This Work

The motivation to perform this work has been found through the common problem present in the daily routine of the shipyard around the world, the welding-induced deformation on steel panel of the ships. Assisting a suggestion made by the Polish shipyard, some experiments have been carried out in order to collect the datas for understanding this issue in the welding line at shipyard.

Every time when the rework really does take part inside the normal production flow, it can be understood that something goes on the wrong way and abnormal phenomena has occurred. Whereas the production works for producing, some efforts must be done in order to avoid such problems and consequently some important achievement might be reached such as: reducing rework, saving money, time and man power.

In this current case, an analysis to have a numerical prediction in terms of mathematical equation involving some welding parameter as well as some pressure parameter which were considered relevant for this study, has been carried out. The analysis is about the problem related to the deformation after SAW of ship panel made by 5-mm-thick steel plates using statistical tool. This study mentions some routine for modeling of the problem as well as the modeling of the experiment. It means data collection, data processing and analysis of the results obtained. These might be considered as the outstanding characteristics of the present work.

All the data used in this project has collected at Polish Shipyard and they were achieved according to the condition exposed on AppendixA1.

Furthermore, some expectation around this Master Thesis may be considered as a result:

- mathematical equation to understand the deformation of 5-mm-thick steel plates;
- one feasible way to predict such deformation at workshop, showing step-by-step the methods used and results achieved;

- proposes of future works related to cost down due to reducing straightening process.

Despite of the fact that the entire experiment uses real datas from the Polish shipyard, some restriction must be kept in mind before the model might be considered. Hence after this mathematical and statistical understanding, new other trials for validations of the results have got be carried out, respecting the results reached and exposed in this work. This validation aims identifying the possible incoherencies in the present model, correct them and then guarantee the accuracy of those equations in the future using.

1.3 Structure of this Master Thesis

The main issues related to the proposed theme and also the details about the experiments and the measurement as well as the results obtained and pertinent comments are described along of this work as follow:

Chapter 2: Literature review. During this chapter some words about the welding process, welding problem, the scenario of the shipbuilding industry nowadays and some comments about these themes. Similarly, some remarks about statistics to reinforce the background to develop the work. In general way, this chapter regards to describe the state of the art.

Chapter 3: Modeling of the problem. This chapter reveals all of the methodology used in the shipyard to organize the experiment, perform the trials, measure the panel deformation and collect the data. This chapter also involves the data processing and shows how the data were arranged to feed the statistical software.

Chapter 4: Results and discussion. This chapter gathers all of the final information yielded from the software and comments about these results are carried out, showing the differences between the results gotten from the two data arrangement.

Chapter 5: Conclusion. Finally, on completion of the work this chapter relates the final point of view about the entire effort and some recommendation for future work are done.

2 LITERATURE REVIEW

2.1 Welding Process in the Shipbuilding Industry

According to Kou (2003), the fusion welding can be described as being a joining process which uses the base metal molten by the high temperature to join the pieces. In order to get this junction phenomena some procedures have been developed along the years and used in several kinds of processes and or constructions as for join metallic material as for join plastics elements.

These industries regarding to production of metal or plastics goods keep the welding process operating in their work flow because the weld process presents several advantage such as:

- reliability on its assemblages;
- high levels of speed during the mass production;
- possibility to implement automated robots to perform the welding;
- yielding standardized parts through the automation;
- high levels of quality.

About the welding processes, some drawbacks also might be seen in the industries and some of them are listed below:

- complex process about the quality control due to several factor involved to perform the welding;
- process needs skilled operators to perform it;
- expensive and complex infra structure when automatics welding process are needed;
- possibility of high levels of risks and loss in case of welding failure during the welded part functioning (steel structure of civil building, vessels, oil platforms or automobile).

In their work, Deng at all (2002) say that in shipbuilding is really necessary considerable assemblage between large blocks and due to the fact of these blocks are typically all-welded thin plate structure, during the fabrication some distortion may occur by virtue of several causes including the cutting of the plates and pieces as well as the welding junction along of them.

In specific area of construction, like shipbuilding, the welding process is extensively used due to several advantages and regarding to the significant demand to use steel or aluminum alloys on structural pieces of the construction. Ship hull, watertight bulkheads, decks, bottom, girders or stiffener, for instance, are commonly built in steel. Therefore thousands of tones of welding material are expected on one single ship to connect all of this material together.

As long as the welding procedure is used in the shipyards, one important matter remains in the workshop atmosphere – residual stress after welding.

2.2 Usual Types of Welding Process in the Shipbuilding Industry

Several ways to connect parts are available in the market. However some consideration to chose one of them might be done before.

Characteristics to define the type of welding:

- type of the junction that will be connected by the welding;
- type of material which will be welded;
- limitation of the layout production ;
- thickness of the material and;
- purpose of the welding.

Considering these issues and many others, is possible to make choice among several kinds of welding, such as:

- GMAW

Gas Metal Arc Welding is characterized by process of junction of metals, through the electric arc established between the pieces and the consumable wire (addition material) and protected by the shielding gas (this gas can be active or inert), Fortes (2005). The wire used to help the connection is fed regularly and it is molten by the heating generated by electric arc during the welding. The shielding gas is used to protect the molten material from the atmosphere during the process and it might be inert, for MIG welding or it might be active, in case of MAG welding.

According to Kou (2003), the shielding gas used during the GMAW can be Argon or Helium or even their mixtures, in case of nonferrous metals as well as for stainless and alloys steel. The shielding arc with Argon, for instance, helps to produce a stable transference of the droplets of molten material. However, depending on the material of the work piece, some additional gas, such as CO_2 or O_2, may be included in the Argon mixture in order to reduce the spatter or the undercutting at the fusion lines.

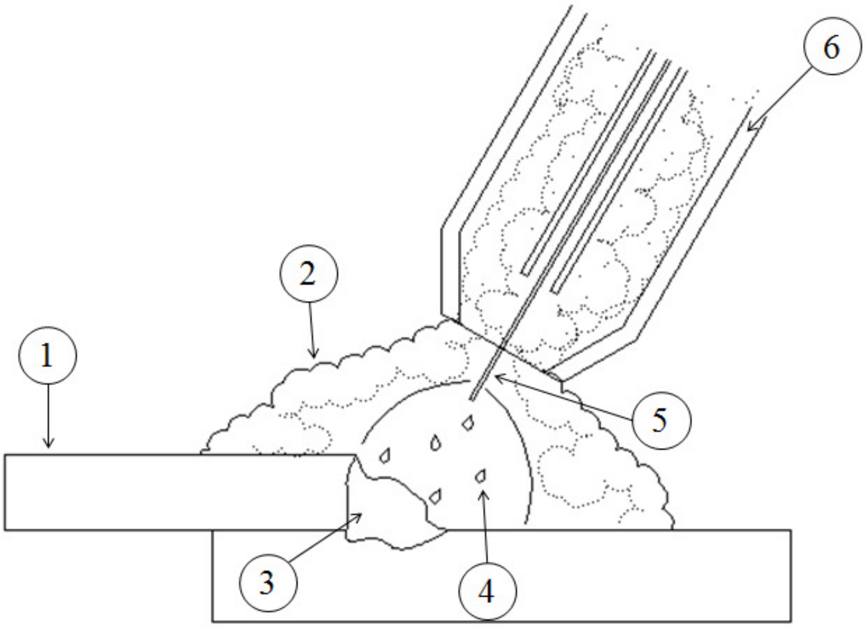


Figure 2.1 - GMAW Scheme.

In Figure 2.1 is possible to verify the elements involved during the GMAW, such as: 1. Work pieces; 2. Shielding Gas; 3. Molten Pool; 4. Droplets of molten metal; 5. Consumable wire; 6. Welding nozzle.

- SAW

According to Törnblom (2007), SAW has a high level of productive. It is a mechanized welding method that can be done as with a single electrodes as with several ones at the same time. The electric arc burns underneath a layer of protective flux which melts at the vicinity of the arc and produces a solid slag on the weld, as a result. The non-molten excess flux is recycled. During the operation the arc is not visible because it is hidden under the flux therefore the name.

Considering the work from Kou (2003) also the work from Fortes (2004), is possible to state that similarly to GMAW, Submerged Arc Welding also joins metallic parts through the heating provided by the electric arc. Nevertheless, the shielding gas used during the GMAW is not required on SAW once it throws a granular flux on the work piece with respect to protect the weld pool from the atmosphere.

The granular flux is continuously deposited on the pieces during the welding and part of this flux surrounding the electric arc is melted because of the heating, generating a kind of solid slag which directly protects the weld pool. The rest of the granular flux remains like powder and it can be reused for the next operations.

Due to the fact that the weld pool is totally hidden by the granular flow, during the welding there is no smoke, spark, spatter or electric arc visible.

This kind of process has many advantages concerning:

- deposition rate, once this method allows using two or more different electrodes in tandem;
- because of the deposition rates, thick plates can be welded;
- without smoke and spatter, as a result the process yields a clean weld.

And certain drawbacks can be considered:

- due to the granular flow and expressively weld pool, the process is limited to work on flat position;
- due to the high welding current generated can increase the distortion of the plates, especially for thin plates.

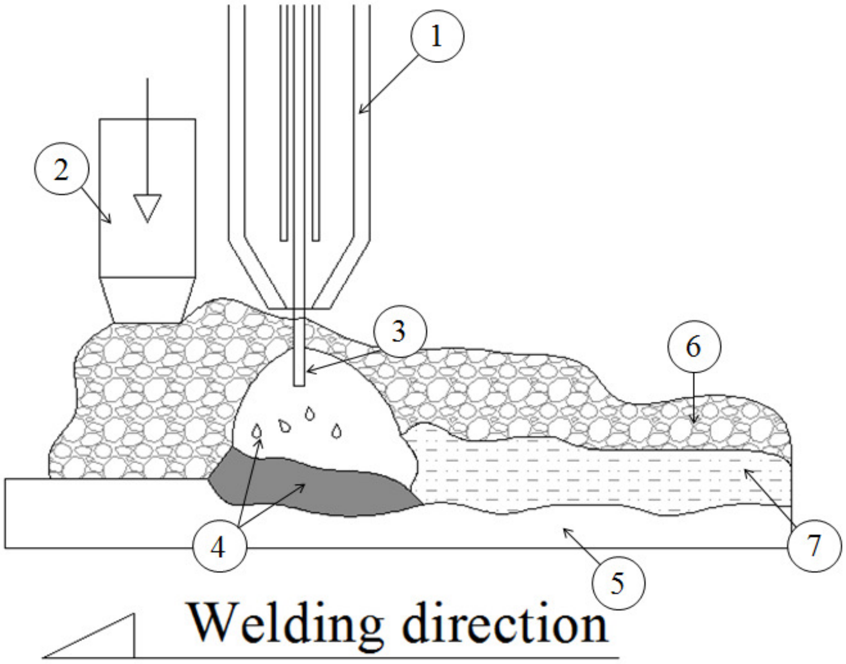
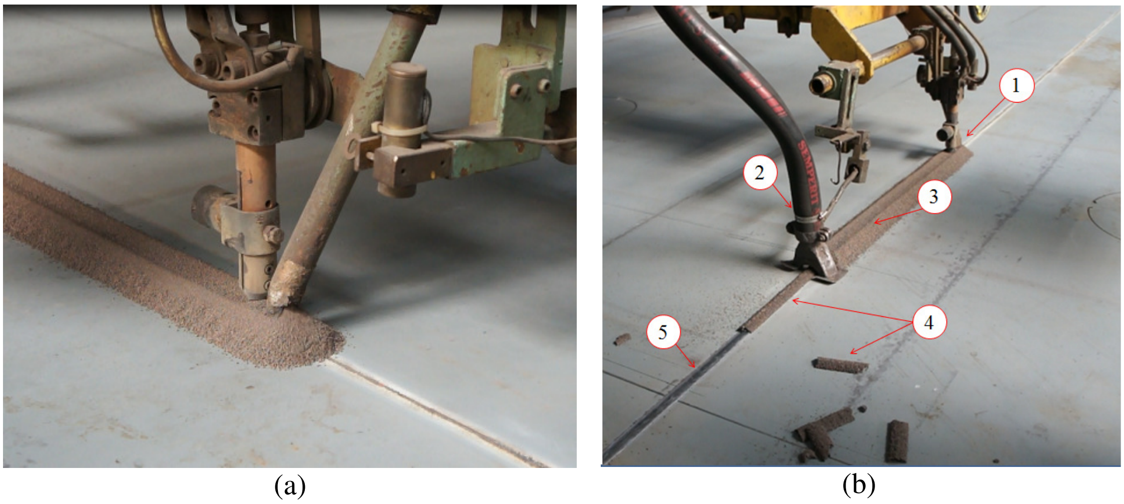


Figure 2.2 - SAW Scheme.

In Figure 2.2 is possible to verify the elements involved during the GMAW, such as: 1. Welding nozzle; 2. Granular flux feeder; 3. Consumable wire (additional material); 4. Molten Pool and droplets of molten metal; 5. Work piece; 6. Granular flux protecting the welding; 7. Granular flux solidified covering the welding seam (Slag).

As long as the welding facilities are traveling on the work pieces and welding them, part of the granular flux melts and other part remains on the powder condition. Therefore, a vacuum gadget inhales the granular flux after the welding nozzle passed by and then all of the remainder powder is driven to the granular flux container and stored meanwhile the solid slag stays on the weld seam. After finishing the welding, the solid slag is removed and the weld seam can be seen, as shown in Figure 2.3:



(a) (b)

Figure 2.3 - General view of SAW operation.

The SAW is widely used in the shipbuilding industry and is possible to verify it detailed in Figure 2.3 (a) and similarly to the Figure 2.2 but on real terms its characteristics in Figure 2.3 (b): 1. Set of welding nozzle and granular flux feeder; 2. Vacuum sweeper gadget working; 3. Powder layer of granular flux; 4. Solid slag of granular flux solidified; 5. Weld seam without the protection.

2.3 Usual Types of Junction

Like the need for adequate welding equipment as the need for adequate geometries to be connect the members. This point in question is also important to determine the quality of the connection.

The type of junction is a determinant factor to define which kind of welding process will be used.

As an example is understandable to mention:

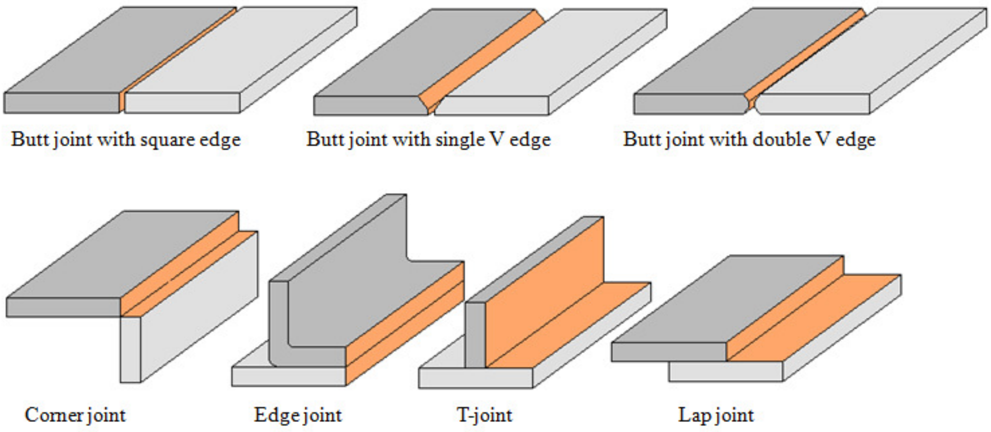


Figure 2.4 - Usual types of welding connection.

All of the shapes for welding have a specific purpose to be done as for geometry need as for safety and quality reason. In Figure 2.4 some of the most usual types of junction used in shipbuilding are shown and the orange faces highlighted are the local where the weld seam will take place.

- Butt joint: it is widely used for connection between plates from the hull, decks, bottom and so on. The butt joint connects two plates laid side-by-side through their top. For this edge that will be used during the welding, it can be modeled aiming offer strength to the connection or improve the welding performance about the penetration, for example.
- Corner joint: it is characterized by the coupling over two plates placed perpendicularly from each other, creating a right angle in between their top. The welding is performed directly on the square angle.
- Edge joint: it can be understood through the welded part being the two top faces.
- T-joint: Consists on linking two pieces of metal positioned on the perpendicular way. However, differently from the corner joint, the welding will take place on the side part of the plates instead of their top. This kind of shape has been largely used on fabrication of girder (the connection web-flange) and on junction in between girder and panel shape in shipbuilding.

- Lap joint: is defined as two plates overlapped and the weld seam is performed on top of one at the same time on face of another plate. This kind of geometry is easily found in the shipbuilding industry, in general small pieces along the hull.

2.4 Few Other Welding Characteristics

To arrange a welding process and be able to extract reasonable results from this is necessary to understand a few characteristics and be aware about its consequences on the work pieces which will be welded. Some of them have been commented earlier, such as: type of the welding process or the shape of the geometry. However other issues are equally important when the welding process is under evaluation.

From this point of view, is feasible include in this list of important welding characteristics the following aspects:

- heat input;
- residual stress;
- welding deformation.

According to Awang (2002), he states that besides the residual stress on welding distortion, it is necessary to understand the effect of welding parameter which contribute for the occurrence of the phenomenon, such as: welding sequence, welding facilities, welding joint geometry and so on.

- Heat Input:

The heat input might be estimated as being one of the most important factors present at the welding process and according to Tsai at all (1999), besides it is amongst the important variables related to the quality of welding, mainly with respect to the warping problem found on welding fabrication. When issue related to the quality is mentioned, problem comes up to be checked out. Heat input makes influence on the dimensions of the welded object because it applies energy enough to melt the additional material and the work piece. Such energy may generate local distortion, as informed by Deng at all (2002).

An interesting remark present in the work done by Wang at all (2009), mentions that in their results the transverse shrinkage in weld centre is bigger than at points nearby the starting or extinguishing arc welding and this fact is strictly related to the amount of the heat input and smaller constraints in the centre of the welding rather than in two sides of the plate.

The heat input is the relation in between the welding energy used during the welding operation and the speed of the welding source along the process. Such relation has as a result the unit of energy (in Joules) per unit of length (in mm or cm). Together they are able to determine the amount of heating which will be applied on the metal to melt the base material (work piece) and the fusible wire (additional material).

Thermally speaking, the energy spent to weld the metallic part will define how much the initial structure of the base metal will be disturbed by the heating applied. Hence this parameter must be very carefully analyzed before start the welding process, due to the amount of heating applied and its importance in the thermal gradients generated in the work piece, providing residual stress after cooling and consequently local distortions.

As reported by Funderburk (1999), the heat input is an important parameter also because it makes greater influence over the cooler rates and this aspect may affect the mechanical and metallurgical properties of the base material. Regarding to the cooler rate, Funderburk (1999) affirms that as much as the amount of heating input on the pieces is increased, proportionally the cooler rate decreases. He also says during his work that the heat input has relation with the geometry of the work piece cross section and as much energy is spent on the piece as bigger is the amount of the additional material and base metal melted, resulting in a large welding bead. Therefore the cross-sectional area of the weld part should be in coherency with the heat input planned.

Many others weld characteristics, as the tendon force for instance, are related to the heat input as well as the problem with deformation of large welded structure, as can be illustrate in case of shipbuilding. The compromise to assist the overall dimensions, especially for large welded block which are assembled in the shipyards, is a very challenging task nowadays and as consequence, all the elements involved in the ship construction should be attentively analyzed with intention to avoid problems and consequently costly rework.

- Residual Stress:

As long as the heat energy is necessary to melt metallic parts aiming connect them and this energy reaches out extremely elevated temperatures when compared with the room temperature, inevitably some physical phenomenon will happen inside the work piece. As a consequence, characteristics on this body might be disturbed due to this quick heating and cooling cycle.

A comprehensible work provided by WTIA (2006), explains that the residual stress can be developed on welded structures because of the thermal cycles which happen during the welding process. However, as explained earlier, for welding routines these cycles of heating and cooling behavior are unavoidable. Heating for melt the piece and additional material and then when the heating source passes by an arbitrary point, cooling state.

However, the residual stress existent on material can come from different origins. In case of roller plate fabrication, for example, the compressive behavior from the roller acting on the plates during the production also contributes to generate residual stresses because of the inner contraction inside the material. For that reason, some extra process intending to “relieve” such stress should be done.

Because of the residual stress, a number of problems might occur and as an example of that is reasonable to speak about buckling. According to the work complied by Tajima at all (2007), where is claimed that straightening is a costly and time consuming process which is usually used to fix welding deformation in the shipbuilding industry. They also state that straightening for buckled plate is very difficult to repair and buckling must be avoided whenever possible. In the same work, they say the buckling condition is occasioned because of the residual stress produced during the welding. However, how to avoid such problem if the welding process is extremely necessary during the ship construction? This is one of the many questions which blink in the mind of the researcher who searches for solution to mitigate the welding deformation.

The residual stress is really considered as an important factor during the welding analysis and for that reason plenty of works related to predict it have been developed over the years. As good example of this kind of work are the work achieved by Buffa at all (2011) which shows an acceptable model able to predict the longitudinal distribution of residual stress, comparing finite elements calculations to the experimentally results and similarly another effort from Yajiang at all (2004) is intended to find out the instantaneous distribution of residual stress in order to verify when cracks are initiated during the welding, using the fundaments of finite element method.

Another opinion about residual stress has been found in the work done by Tsai at all (1999), where they define the residual stress as being an unavoidable condition in welded structures. In such situation, during the welding process the heating applied to melt the base metal and the additional material creates a weld bead. During the process, this region which contains the welding bead tends to expand, nonetheless it is constrained by the regions far away of the welding, i.e. the regions which didn’t have any disturbance by the heating and remained at room temperature. As soon as the heating source passes by an arbitrary point along the weld seam, this point received a considerable amount of high temperature and quickly starts to cool down.

Once the cooling state starts, the behavior in the welded area becomes different and rather than tensile mode is possible to recognize a compressive comportment. Nevertheless such situation induces a residual stress due to the fact that the area surrounding heated area does not allow the expansion or contraction of the welded area.

With this same way of thinking, Kou (2003) says that residual stress might be known like thermal stress as well. In case of welded parts, the fact that during the welding process the work piece is submitted to non uniform temperature changes (heating and suddenly cooling behavior), this situation contributes for the condition to develop residual or thermal stresses inside the piece.

From this point of view, to illustrate such situation which occurs inside the work piece during the welding procedure, the Figure 2.5 shows a plate being welded. On this plate, two different moments are chosen on arbitrary way. A transversal section is taken exactly at the moments when the effects are occurring to demonstrate how the internal structure behaves. On one hand (Figure 2.6) the first part (section A-A) is considered crossing the weld seam on the part of the welding was already done and consequently this section is theoretically cooling down, there is possible to describe the events on going such as: 1. Weld bead cooling down; 2. HAZ surrounding the weld bead cooling down. This portion is contracting; 3. Blue narrows showing the contraction trends due to cooling comportment of the weld bead and HAZ; 4. Constrains are given by the colder part farther away from the welding which didn't have any disturbance during the heating. Therefore, this situation generates tensile strains surrounding the welding; 5. Work piece. On the other hand (Figure 2.7), the second one (section B-B) is the cross-section which refers exactly at the point where the welding source is acting i.e. the portion is under extremely high temperature and similarly the figure describes the events such as: 1. Part of the base metal and the additional material are melted due to high temperature; 2. HAZ surrounding the weld bead expanding because of the heating. This portion is acting against the colder material; 3. Red narrows showing the thermal expansion from the welding toward the colder material; 4. Constrains given by the colder part farther away from the welding which didn't have any disturbance during the heating. Therefore, this situation induces compressive strains surrounding the welding; 5. Work piece.

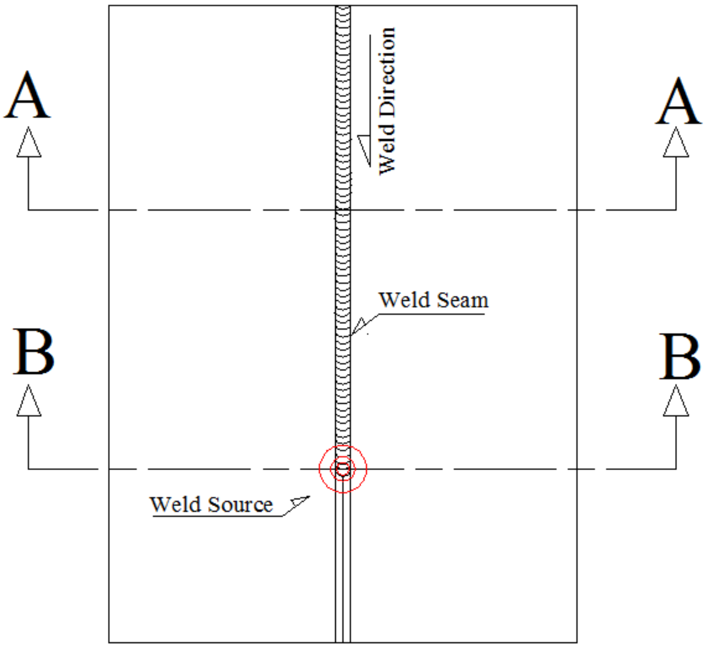


Figure 2.5 - Layout of the plate during the welding.

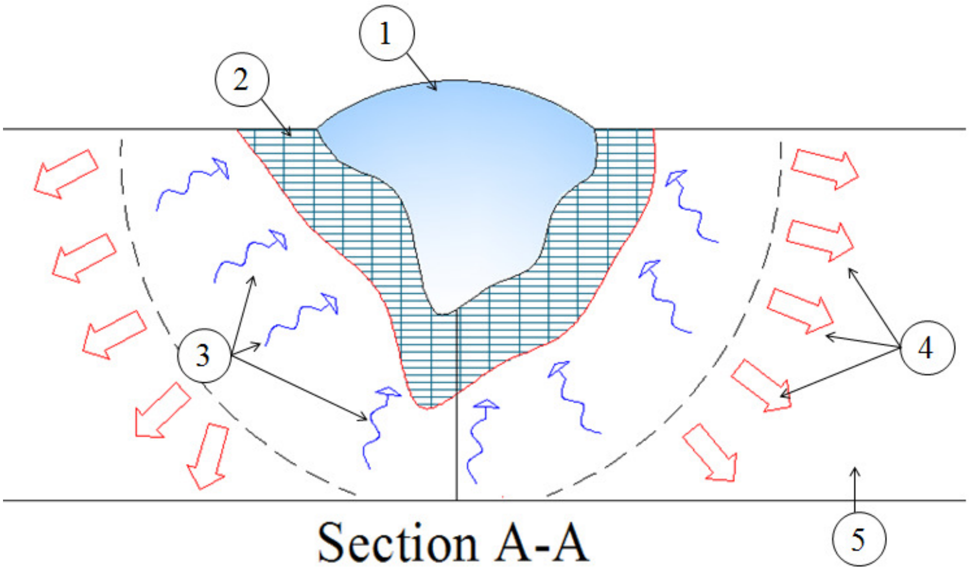


Figure 2.6 - Section A-A: Cooling behavior.

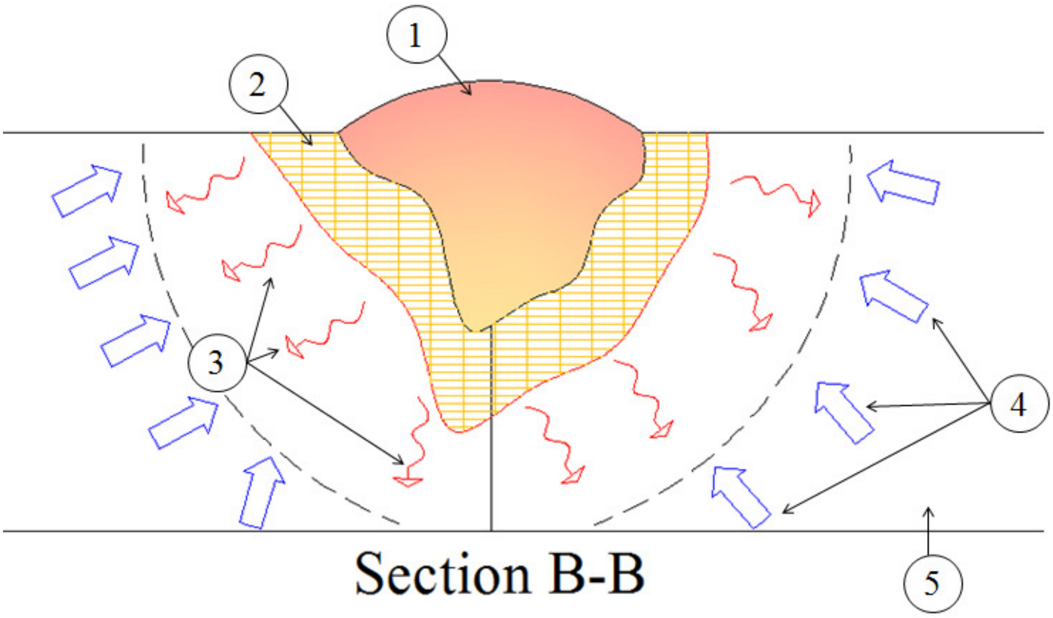


Figure 2.7 Section B-B: Heating up during the welding.

After this induced stress from the welding process, such problems like buckling or localized tensile yielding might be generated.

For that reason, as suggested by Brust and Scott (2007), a proper controlling of the fabrication-induced residual stress state can significantly enhance the structure's life, avoiding expenses distortion correction, maximizing fatigue performance or improving the damage resistance capacity of the structure.

- Welding deformation:

Deformations generated during the welding process are strongly linked to the residual stress and for many researchers welding deformation is an unavoidable problem wherever the welding connections are used.

In the shipyards, considering the work provided by Sukovoy and Kuo (2003), the most representative problem is related to the misalignment between blocks during the hull erection stage. These problems occur due to welding distortion which causes inaccuracies on overall blocks and misassembling among the structural members. Another important remark in their work is regarding to the importance to prevent such problem, they affirm that the welding deformation by far does not interfere only on aesthetical aspect but also to maintain the structural integrity in service.

According to WTIA (2006), distortion in the vicinity of welded joints is a natural and inevitable consequence of the non-uniform heating and cooling that occurs during the welding thermal cycles. These thermal cycles generate thermal gradients resulting in strains thanks to the non-uniform expansion and contraction trends which sometimes exceed the local yield point of the material.

In this case, for thinner plate is easily verified the occurrence of buckling, on the other hand in thicker plates such deformation might not be apparent however the residual stress tends to be higher, WTIA (2006). Therefore the geometry of the work piece is also an important character which must be taken into account to avoid welding deformation, once that the amount of heating applied on the parts might propagate more on thinner plates than on thicker ones. Hence the heating must be in accordance with the work piece cross section area.

Verifying the welding characteristic mentioned previously, is comprehensible consider that the welding deformation is a result of the relation between the welding energy and welding speed (heat input) which creates some residual stress due to thermal expansion and contractions at random, as explained before. To reinforce this idea, assessing the work developed by Kaufmann (2003), is possible to notice it. He says that during the fabrication of T-beam geometry, if the welding is performed only on one side of it, this fact may cause some dimensional distortion and the web plate will bend upwards and sideways. Kaufmann (2003), states that this kind of deformation comes from the intense heat input provoked by the welding process as well as the residual stress released from the plate fabrication or even from the cutting process. These factors will have influence on the shape of the beam.

Similarly, Iranmanesh and Babakoohi (2008) have analyzed the longitudinal shrinkage in plates using butt welding joint as a reference. They realized that in welding process the heating and cooling cycles cause shrinkage in all the elements, as the base metal as the weld material and consequently this shrinkage tends to distort the members and metal structures, once they are coupled by the welding. They also declare that the longitudinal shrinkage is a very important point to be controlled in the welding process, once it can define buckling along the welding line.

The interest to maintain focus on welding parameter is completely understandable because small attitudes may avoid big problems along the workflow, as on welding sequence, as on welding parameter, as on the edge preparation. All of these factors take part during the welding deformation analysis, as described during the conclusions of the Vanli and Michaleris (2001) when they got reduction of the welding deformation and residual stress in their model in terms of -27%, only considering sequenced welding operation.

Nonetheless, different opinion can come up and consider the welding sequence as minor influence in case of welding distortion when all members have no geometrical error and they are fully fitted by tack welding with sufficient stiffness, as found out in the work developed by Murakawa at all (2009). They say that in this case, the welding deformation is attributed to the local shrinkage produced by the welding. Nevertheless, situation like this actually does not portrait the reality of the shipyards since the ship is assembled by different blocks and small parts i.e. when one block comes to be connected, plenty of others are already fitted in the ship.

Another point of view can be seen at the work related to risk-based method for minimizing welding distortion in steel ship production elaborated by Sukovoy and Kuo (2003). They allege that structural misalignment and dimensional inaccuracies from the welding-induced distortion represents a relevant figure related to the production costs. It might be explained because of the corrective processes needed to adjust the welded parts, together with the time necessary to perform such correction. This kind of corrective process usually is lengthy and expensive because is necessary input heating on the parts to bend them on the opposite way of the distortion. Vanli and Michaleris (2001) also share the same opinion when they state that flame straightening, although being a intensive labor and costly process, is the commonly method used in the shipyards to correct the out-of-plane distortion resulting from the welding process.

Few examples of welding deformation in the shipbuilding industry are shown in Figure 2.8:


(a) (b)

Figure 2.8 - Examples of welding deformation.

In Figure 2.8 (a) is possible to visualize the deformation upward on steel panel still on the welding line and in Figure 2.8 (b) shows the upper deck plate deformed before block assembling

Hence, welding deformation is an issue present in the shipyards which must be analyzed and mitigated whenever is possible and if even with the analyses the problem occurs, so it must be corrected.

2.5 Few Words about Statistics

With a view to minimize the undesirables effects of the problem in the work flow or wherever the problem might be placed, it is possible to check in the available literature that over the years several methods using the most diversified tools have been develop to identify these problems, understand, correct or, at least, mitigate them. Reaching this purpose, some inconveniences in the work flow may be eliminated and as a result improving the performance of the process.

Regarding to the welding problems, FEM are habitually used to simulate and investigate the residual stress distribution along the geometry and then to suggest some modification to improve the process, for instance in the work elaborated by Yajiang at all (2004) where they figured out through the FEA that the distribution of the residual stress in the direction of the width of a certain steel plate has greater influence on cold crack formation. Works like this have been developed and provided good results, helping out the manufacturer to avoid problematic situation.

From the same point of view, statistical tools are well harnessed in case of process analysis, especially for solving problem or even for process management. It also can drive the research toward the understanding of the process and with this some consideration relative to the problem might be achieved, in addition the comprehension of the current situation might be done in order to minimize the effects or increase the productivity capacity. As an example, it is possible to be verified in the work developed by Sofuoglu (2006), where he suggests low level of lubricants to reduce the frictional effects, high level of material type, moreover specific type of plasticine intending to improve the flow behavior of plasticines. He got this conclusion from statistical background yielded by DoE and the results specifying elements, material and so on were gotten through series of experiments.

Safely identification about the effects and the possible causes using statistical tools can be achieved because of the logical concept adopted in the cases. Furthermore, during the approaching an interesting stage to figure out the cause and effects inside the process is related to the experimentation, as verified in the work of Sofuoglu (2006).

The statistics, in an overview according to Johnson and Bhattacharyya (1987), deals with collecting informative data, understanding these data and elaborating conclusions to explain the object under study and it can be applied in all of the case where there is input, processing and outputs. The scheme of input-process-output data allows the experimenter the understanding of the process i.e. how the modification existents in the "process" acting, what are the factor responsible for such modification or even better, what are the factors responsible for undesirable output. The experimentation helps the experimenter getting these information.

This concept to experiment factors and verify the results may be seen in Figure 2.9 where a simple sketch of the approaching to improve a general process is described.

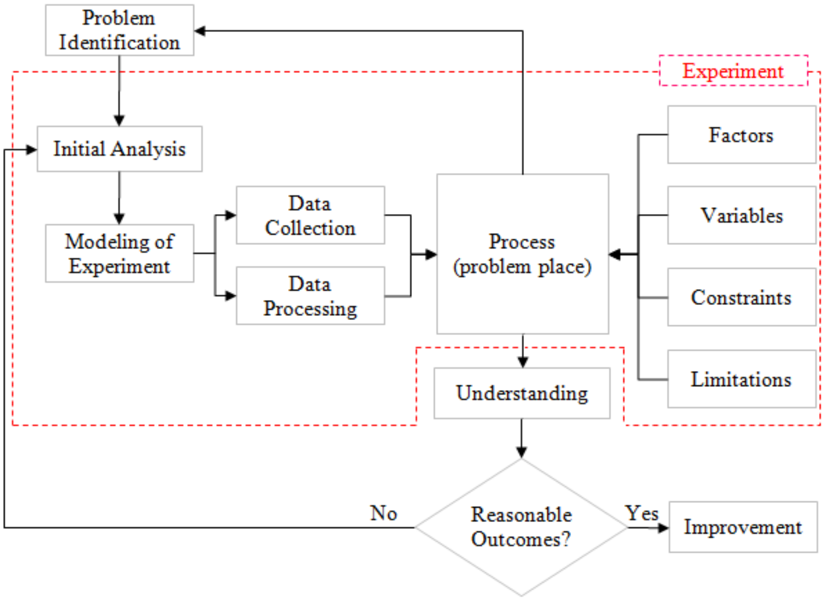


Figure 2.9 - Sight of input-process-output scheme.

The experimentation is focused on explanation of the process or some behavior throughout the actual results acquired from the object of the study (the process) and it needs to be carefully modeled in accordance to each specific case, it means that all of the characteristics of the process to be analyzed should be taking into consideration, in the interest of avoid inaccurate results. For this reason, the problem identification and the initial analysis are described in **Erro! Argumento de opção desconhecido.**, together with the factors, variables, constraints and limitations of the process.

After this initial evaluation, the model to evaluate the object under study should be reached involving the main factor and then the experiments can run out throughout the process which consequently will provide the outputs to be analyzed critically. From these results, some changes might be done in the model or some conclusions may be drawn intending to justify the functioning of the process as well as make some inferences to improve the general process.

Just to illustrate the experimental scenario, one case regarding the distortion on metallic parts generated by the induced-stresses from the heating of the welding process involves many factors and those factors somehow, must be taken into account during the modeling of the experiment, aiming a consistent and reliable analysis.

It is really important to know what are the factors existent in the process that make real influence in the final output, from the analysis point of view i.e. those ones which are contributing for the problem occurs. For this example is reasonable to point out only some of the various relevant factors which contribute for this kind of problem:

- weld energy (current and voltage);
- weld speed;
- weld type;
- thickness of the plates and;
- boundary condition during the welding process.

How to consider all of these factors during the analysis and to organize the data or compute them? To answer these questions, many statistical tools and softwares are available and surely some concepts must be considered with intention to make a proper breakdown about the situation.

In this work, some experiments and evaluations were carried out under design of experiment (DoE) methodology.

Some statistical fundament has been used to get the model and consequently the results for the analysis of the deformation after SAW on ship panels.

2.6 Design of Experiment (DoE)

As mentioned before, some statistical tools and different approaches are available in the market to be used in analysis as for process as for problem or even for management. It is possible to find many scientifics and industrial works being developed nowadays under those methodologies and using one single or more than one statistical tool together.

As examples of statistical approach and some tools are coherent to mention:

- ANOVA;
- Regression Analysis;
- Correlation;
- DoE;
- SPC.

There are plenty more of others tools that might be shown in this list, however one specific approach will be used and discussed during the current work intending to predict the welding-induced deformation – Design of Experiment.

Design of experiment is a methodology used to planning a series of structured experiments and then to determine the data to be collected, the way or how it can be gather. Such organization goes towards to the best statistical condition, on the easiest and fastest way and for the least amount of money possible for the experiment i.e. avoiding data misunderstanding, extra costs and reworks. It can be emphasized by Sofuoglu (2006) where he states that by using the statistical experimental design is possible to quantify the influence of the main factors and the most importantly, the interaction between them in the process.

As reported by Galvanin at all (2010), the model-based on design of experiment might be considered like an important and well defined approach for the quick but robust assessment, moreover the development of the model and its characteristics, potentiating the information in the experiment and reducing the sources of mistakes.

Another similar point of view about DoE can be found in the work developed by Franceschini and Macchietto (2005). In their work the authors defined the Model-based experiment design as being a assistance tool as for the modeler as for the experimenter in elaborating experiments that will have informative data, in a statistical way, for use in parameter estimation and model validation.

A work performed by Galvanin at all (2008) has related the improvement about the experimentation with respect to the definition of the model for the experiment and because of this, they states that the design of experiment allows the determine the “best” experimental conditions to adopt in the experimentation in order to increase the informative content about a process being studied.

In all the cases, some improvement in terms of maximization or minimization cam be achieved using the statistical tool design of experiment. Hence, DoE might be defined as being a kind of helpful tool to be used for experimenter when some ideas come up to improve some process or when problematic scenario should be solved. However a number of experience and knowledge about the process or environment where the improvement will be applied is required to use the DoE during the experiment as states Franceschini and Macchietto (2005). They affirm that for using this methodology is necessary someone (modeler or experimenter) to choose the order and the parameter to be included in the DoE, additionally the measurement issues and points related to it, on the other words, who will measure the outcomes, how it could be measure or even how many times it needs to be measured.

As is possible to realize, design of experiment is an interesting tool to analyze once it is systematic. It can also be applied in different fields, aiming minimize the variance and maximize the results.

Summarizing, the need to identify real cause of the problem or of a problematic situation, especially inside of the fabrication’s border, for example, makes a number of relevant remarks being considered. For this reason, a systematic operation used during an experiment helps to carry out the analysis under practical and regular advance. Moreover, it organizes the general situation making it clear enough, facilitating the decision maker to arrive at a coherent conclusion about the actions that should be taken to solve or decrease the consequences generated by the problem.

3 MODELING OF THE PROBLEM

3.1 Introduction

During this work, an attempt to predict the welding-induced deformation on 5-mm-thick plates used in ship steel panel and welded by SAW has been carried out. Unlike the most known method used for welding analysis by many researchers, FEM, this current work adopted a statistical approach with a useful tool, Design of Experiment (DoE) and aided by the statistical software Design-Expert® (DX8).

The values and results achieved as well as the ways to approach the problem were attentively presented during this work based on statistical methods. From the methodology to analyze the problem defined, results must be drawn to be expected intending to evaluate the final results and check if they were reasonable or not. Somehow effort must be done toward the stipulated targets. But, which targets can be considered or what can be measured? These and many other questions came up to be answered and then start to figure out what is needed to be done.

From the idea to perform a DoE to predict the deformation in steel plates, an experiment should be organized and all the factors related to this phenomenon defined in order to have a consistent result. Anyhow to perform any kind of experiment in the industry, for instance in one like a shipyard, especially when hindrance like culture and languages barrier are truly live, by far it is not an easy task, many things must be set up and discussed before, during and after of any action. Therefore, intending to overcome such difficult and to get the relevant characteristics for the proposed DoE, a temporary team was formed in the shipyards and the strategic peoples were convened to join this idea. Under general overview, the Figure 3.1 shows the main character of this scheme to start the experiment together with some of their tasks.

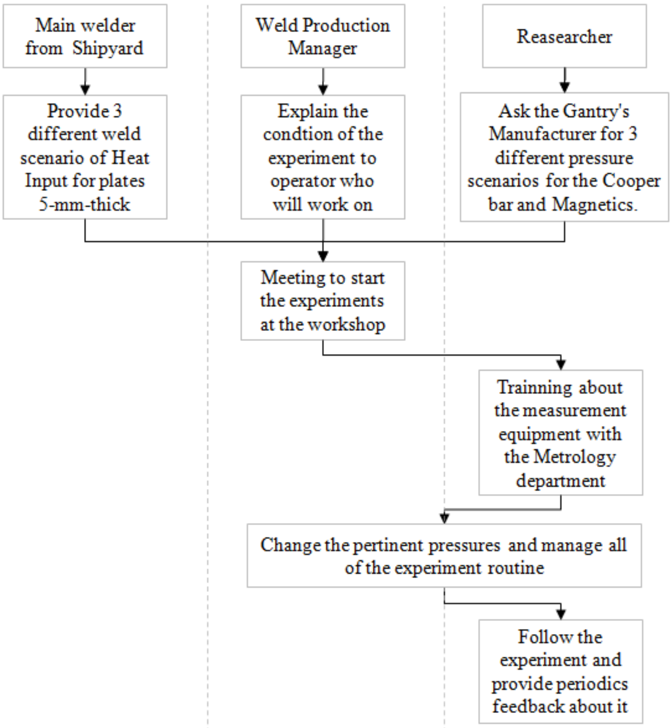


Figure 3.1 - Scheme to develop the DoE in the Shipyard.

After a general discussion for task division, the parameter of welding and pressure already defined the main sketch of the daily routine of the experiment has been defined and it is exposed in the Appendix A1. There is possible to verify the table where all of the parameters which would be used during the experiments are described, sequentially and respecting the side of the panel, in the end yielding 27 different welding condition and consequently 27 different trials. Over there is possible to check the values of the wire diameter wire used for the welding process with SAW technology, current type, the pressure applied on steel plates by the copper bar and the magnetic during the welding operation and finally the data of each trial as well as the quantity of the plates welded on each panel.

Apart from this table, some others information were used during the weldment of the panels considered during this experiment, however such information were not revealed in this work. It is valuable to say that during this work, due to the tight time to perform the experiments only plate 5-mm-thick has been taken into consideration.

The following subchapter of the section Modeling is related to:

- Definition of the problem: describing the problem itself, how it occurs and what are the suspicious factors which probably are contributing for the problem occurrence.

- The work flow regarding to the butt welding using SAW: the operation involved in this work flow, how it works, where is placed the problem and the main features of it.
- The measurement procedure and the equipments used: describing about the methods tried to perform the measurement of the welding deformation, details about it and people involved.
- Data processing: finally the topic related to the data processing which holds down all of the analysis about the data arrangement and the software used for the experiment will be explained on detailed way.

3.2 Definition of the Problem

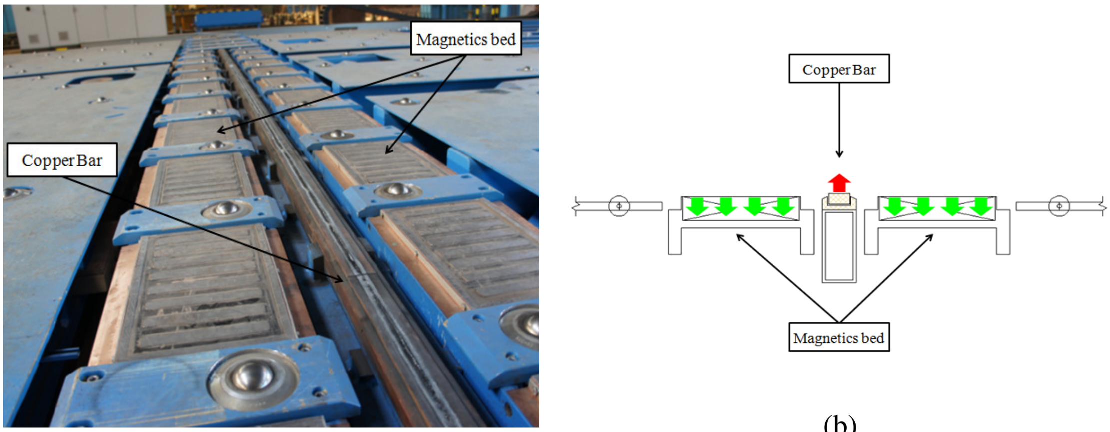
During approximately 3 months, some experiments were organized at Polish Shipyard intending to predict and mitigate the weld-induced deformation after butt-welding with SAW over the plates 5-mm-thick. For doing that, firstly the primary problem recognition was done with some technical aid provided by the shipyard workforce. Hence the general view about the problem is shown in Figure 3.2, the panel deformed at the welding line.

Figure 3.2 - First sight of the problem.

Considering the visual aspect of the panel after welding, the pieces present a kind of non linear behavior along side, expressly nearby the weld seams. Despite of the fact that the plates come in the weld gantry correctly flat, the condition post process demonstrates that the phenomenon commonly occurs during the welding.

Aside from the aesthetical effect, some others undesirable situations however arise due to this deformation. During the assemblage between the sections, plates even during the connection of smaller element onto the panel, for example. Aforementioned such circumstance contributes for the misalignment between the parts and to fix it some other corrective operation is necessary and together with the related costs and the extra time to perform it.

In this case, the reasons for such deformation if the panels come correctly flat to the weld line are searched and some opinions about it took place during the analysis and from the shipyard workforce came the idea to verify the welding gantry facilities used to perform the 1st side butt welding.



(a)

(b)

Figure 3.3 - Welding gantry.

In Figure 3.3 (a) General view about the magnetic beds and the copper bar used on the 1st butt welding and in Figure 3.3 (b) Simple scheme showing the forces acting on the plates during the welding.

Firstly, for the butt welding the plates are placed top-to-top and the magnetic beds pull them in such way to avoid any movement between them. When the tack welding is already performed and the SAW will start, the copper bar is switched on and it applies a constant force against the plates, exactly on the butt junction. Furthermore, this force is contrary to that one coming from the magnetic beds. That scheme of force intends to help the SAW, avoiding leakage of the molten material during the welding, once the plate is not very thick. However, this condition might help the deformation as well in addition to the effect of the residual stress generated by the heating and cooling cycle present all along the welding.

All the procedure done to weld the plates using butt junction and SAW will be explained detailed in the section *Panel Production*, later on.

Thus, the analysis governed by this current work is addressed to the welding and pressure parameter involved in the SAW operation and their effects on the deformation of steel panel. A sketch of the problem is shown in Figure 3.4.

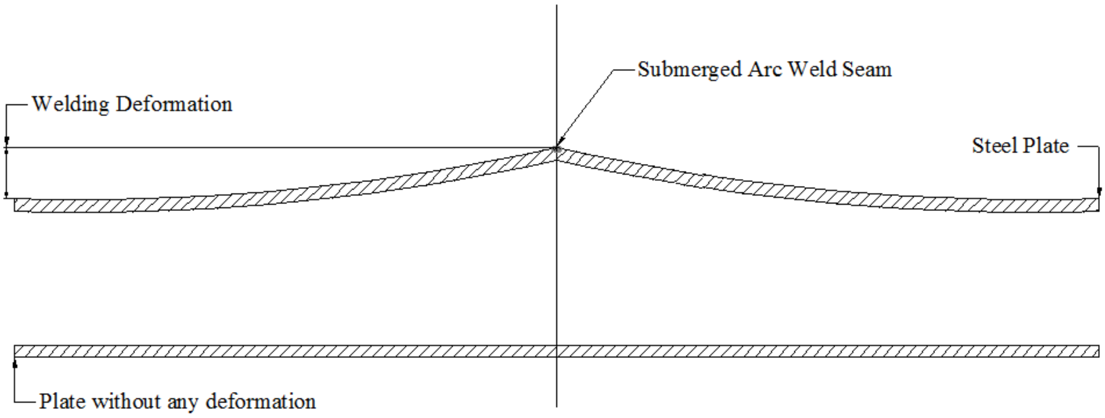


Figure 3.4 - Problem: deformation on steel panel after SAW.

An overview about the problem is shown in Figure 3.5. The panel is laid down on the tracks of the welding line.

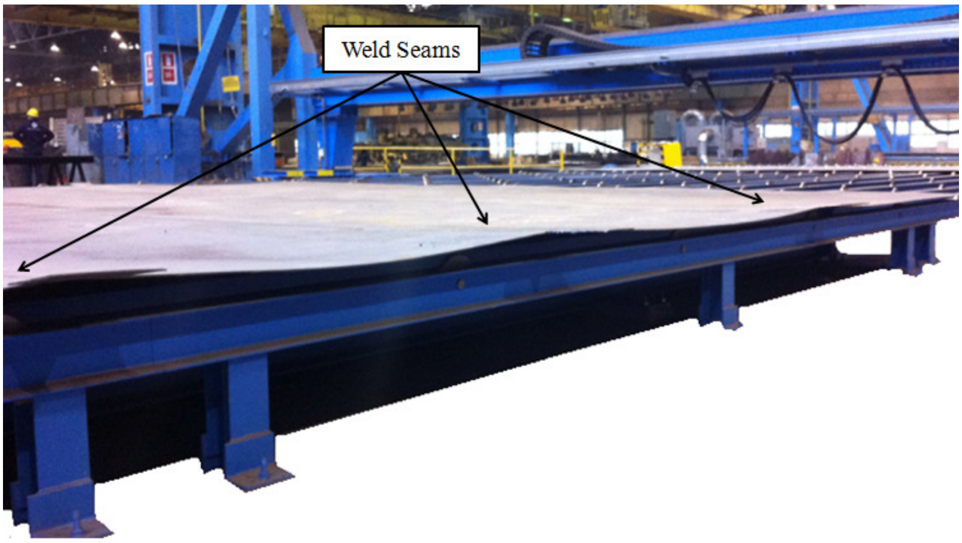


Figure 3.5 - Problem: deformation nearby the weld seam.

From these assumptions, all the work will be toward to analyze, understand and predict the weld-induced deformation throughout statistical concepts. A Design of Experiment will be carried in order to figure out the effects of the welding parameter additionally to the effect of the pressure coming from the copper bar and magnetic.

3.3 Experiment

3.3.1 Panel Production

In order to get some reasonable data from the welding process to feed up the statistical software and provide interesting outcomes to predict the distortion after welding at ship panel, there is no better place than a real shipyard.

Using the partnership between a traditional Polish shipyard and the West Pomeranian University of Technology in Szczecin was possible to propose, at Polish shipyard, a kind of project of improvement and research. The Shipyard has proposed a theme for analysis of the deformation after butt welding for steel plate of the ship panel with SAW.

Such investigation should be developed during approximately 6 months, being 3 out of 6 at the shipyard and 3 left at university. Those 3 first months at shipyard are supposed to structure the research about data collecting, to enable the researcher to be acquainted to the ship building atmosphere as well as the processes technique used to i.e. this time should provide some experimental data in order to processing them and as a result getting a reasonable outcome able to predict and/or at least help to define the main variables which can cause the deformation on the panel at mentioned condition. That data collecting and data processing worked under supervising of the university and the shipyard.

Such propose might be seen as a statistical procedure since the condition to perform the experiment lays on the changes of the main parameter involved on the welding process and the welding facilities as well, and it can be explained in the following diagram:

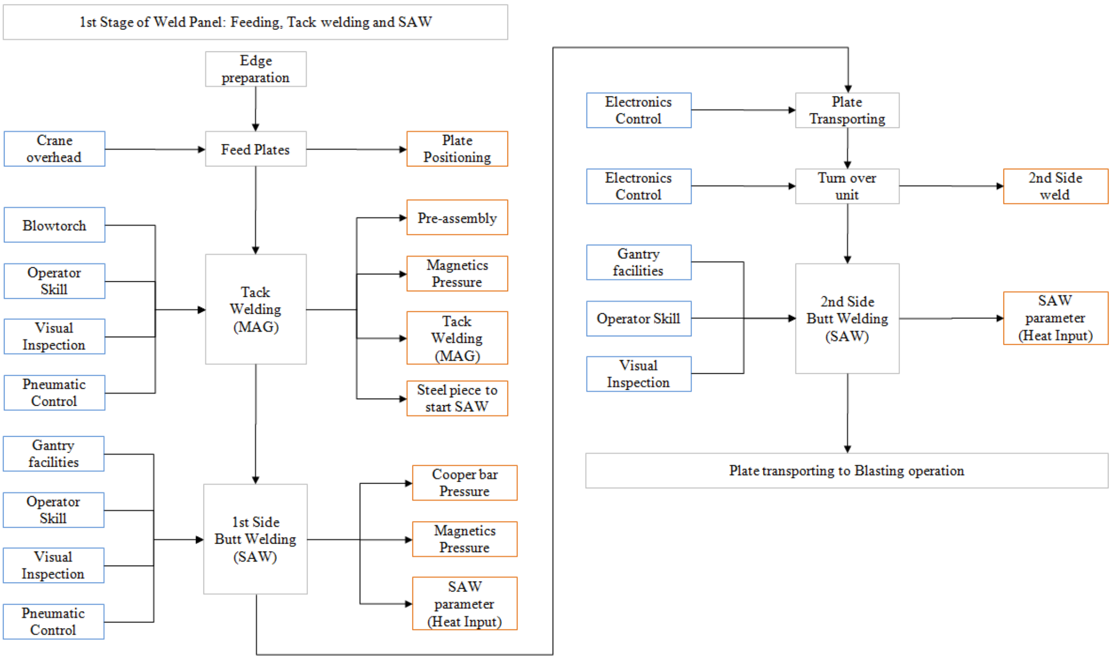


Figure 3.6- Prefabrication workflow.

The diagram showed at Figure 3.6 is composed for the main general steps used to perform the welding at work shop. Those steps are unfolded below.

- Edges preparation

Before start the welding procedure, some requirements are stipulated to process the plates and get the desired result. Checking about the raw material such as weld wire, protector blanket and the levels of the cooler liquid tank are usual task carried out by the operator every single morning before their jobs. Initially, the person who is in charge of the production takes place at a short meeting where the targets for that day is explained and discussed with all of the people related. Drawings about the panels, methodologies to assembly or constrains about them are put to discuss.

Afterwards the worker assuming their places and the process begins. The first step, as mentioned before, is to prepare the edges in order to remove part of the anti-corrosion coating (used as a plate protection) from the steel plates using a pneumatic countersink and supporting the plate on racks.

Figure 3.7 - Worker acting on edge preparation using pneumatic countersink.

After reams down all of the plate edges, the operator asks the overhead crane's drive to transport the plate to the welding line.

- Feed plate

Since the plate has already its edges cleaned, that plate is able to receive the submerged arc welding (SAW).

The welding line facilities is able to weld panel with maximum dimension of 12x12 m i.e. 5 plates and 4 weld seams. However smaller geometries are also possible to work on. Those prepared plates are driven by overhead cranes, using magnetic attachments which are able to lift the plates up, from the racks of preparation until the 3.2m long first roller field placed at beginning of the welding line. It works as a kind of loading table. From this point on the crane is not necessary for while and all the electro-mechanisms can positing the first and the second plate to the correct position for the butt welding.

Figure 3.8 - Overhead crane transporting the plates.

Nevertheless, before the butt welding some adjustment are needed in order to guarantee the perfect junction between the plates.

- Tack welding

At this workstation the plate has its edges prepared already and it is placed at the welding line rollers.

First of all, the operator makes an alignment between the plates. For this operation, he uses electro-mechanics devices driven by joysticks at the main controller panel. The first plate slides on the welding line rollers and overcome the cooper bar placed transversally to the main axis of the welding line. Then that first plate is positioned after the copper bar limits helped out by the wheels and rollers along the line and clamped by the right magnetic bed. After the first plate is already positioned properly at the right side of the copper bar, the second plate comes up to the line rollers in order to perform the right junction (top-to-top) between two plate edges. Such condition is possible due to gantry facilities. A summarized sketch is shown at Figure 3.9, where (a): Initial stage: 1. Copper bar and 2. Magnetic bed; (b) First panel aligned and second plate approaching; (c) SAW operation; (d) Third plate approaching.

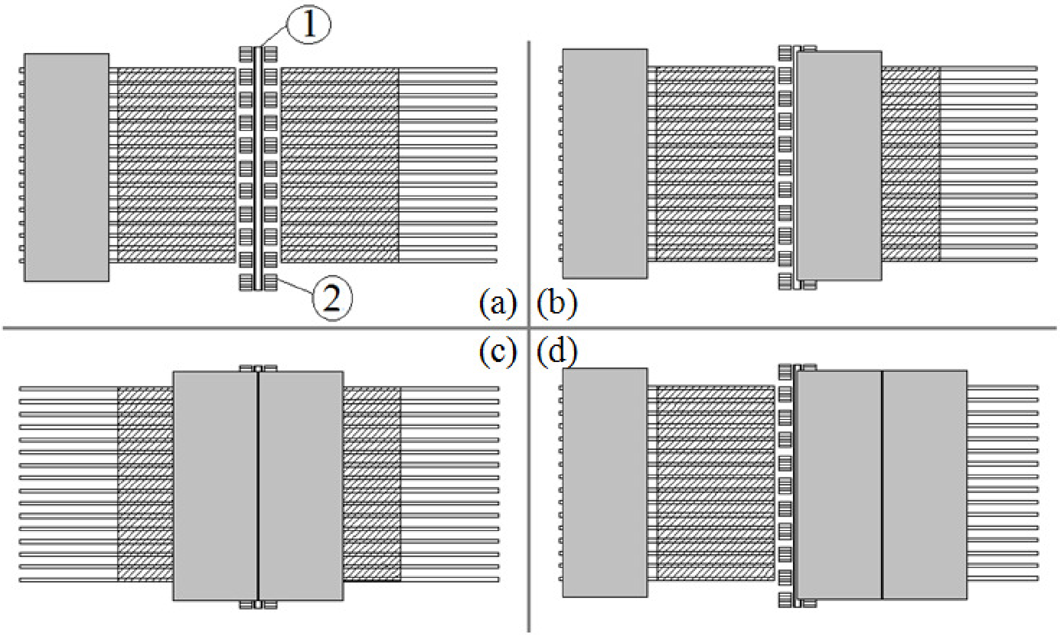


Figure 3.9 - Scheme of the welding gantry.

Concerning the magnetic pressure and cooper bar pressure, both of them were set up by the researcher during the period of the experiment. Before that, all of the plates have been welded under same pressure condition. All of the manometer and pressure facilities were locked out at the pressure panel far away from the operator commands.

Once the plates are placed over the copper bar and clamped by the magnetic beds, the tack welding operation is carried out. However some imperfections such as small deformation along the edges oblige the worker to straighten those deformation using hammers in order to fit the plates properly at the line and allows the operator perform the tack welding.

As long as the workers hammer the plates to repair the misalignment between the plates, gradually they perform the tack welding using MAG (Metal Active Gas), as shown in Figure 3.10 (a) and (b). Therefore, this work station needs really skilled and experienced operators working on, due to the inspection and evaluations necessary during this tack welding which are in fact done based on their abilities and feeling.

(a) (b)

Figure 3.10 - Tack welding operation.

The next step after the tack welding along width of the plates is to attach two small pieces of steel in both plate extremities in order to allow the starting SAW.

- 1st Side butt welding (SAW)

When these two plates are already connected by the tack welding, they are available and ready to receive the SAW from the first side plate operation.

Before start the SAW, the worker uses a simple alignment system, called seam tracking system, for the weld head to guide it during the process. Its propose is to assist like an adjustment device for the route which the head will follow in order to guarantee the weld seam at the correct place in between the two plates edge. After this alignment, the SAW is performed according to the conditions described in the AppendixA1, where all of the condition for pressure of the magnetic and cooper bar and the condition for heat input are detailed. Small sketch is shown at Table 3.1.

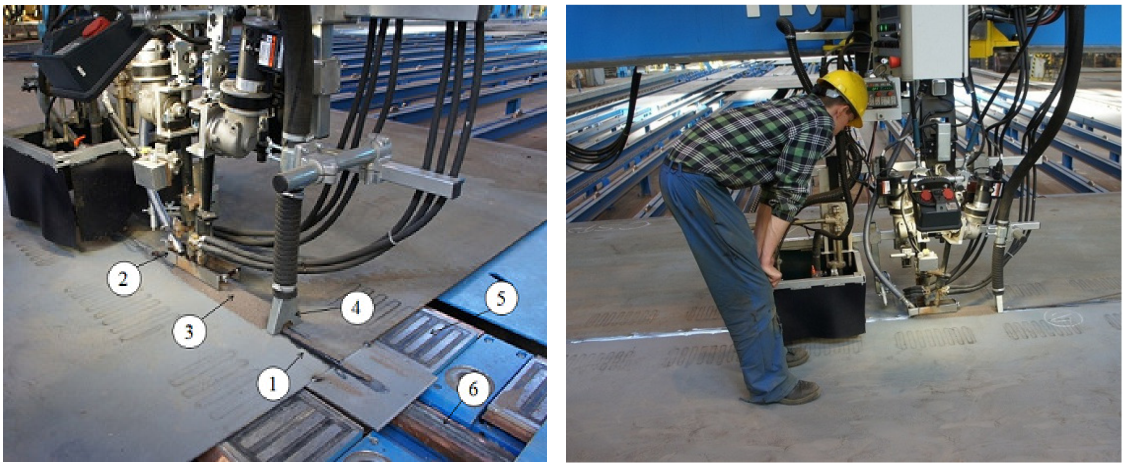
Table 3.1 - Set of parameter available for the worker.

Side	Trial	Wire diameter	Current	Voltage	Speed	Heat Input (Calculated)	Magnetics Pressure	Cooper bar Pressure
		[mm]	[A]	[V]	[cm/min]	[kJ/cm]	[bar]	[bar]
1	1	4.0	400	33	65	11.0	0.35	1.0
2		4.0	430	34	80	9.6	-	-

With this data available, the worker sets up all of them related to the SAW and the researcher sets up those ones concerning to the pressure of the cooper bar as well as the magnetic bed.

That process usually takes in between 12 to 20 minutes. It depends on how wide the plate is. As mentioned before, the welding line supports 12x12-m plate as a maximum size, however smaller dimension are acceptable as well. In this current case, the dimension has varied from one plate to another due to tight time to perform all of the experiment, some adaptation have been considered along this period aiming to fulfill all of the data collection hence the plate dimensions, in the majority of the trials, were not the same.

At the first side is welded following the description above and helped by magnetic bed and cooper bar pressure. In Figure 3.11 is possible to verify the welding carriage in SAW operation and in (a) 1. Weld Seam and SAW slag; 2. SAW head; 3. SAW Coating powder; 4. Hoover; 5. Magnetic bed; 6. Cooper bar and (b) Visual inspection during the SAW.



(a) (b)

Figure 3.11 - Welding in SAW operation.

After finish the operation, the plate should be cleaned by the operator due to slag from the SAW.

- Plate Transporting

Since the first side weld is finished, the next step is to lead the panel (all of the plates welded) to the turn unit platforms in order to turn out the panel i.e. turn it upside down. This transportation is done by the set of roller beam, carrier and a chain conveyor coupled to the welding line. That set is fixed at the panel and then the system pushes or pulls it ahead for the next operation controlled by the operators. In Figure 3.12 (a) is possible to realize 1. plate waiting for transportation; 2. carrier; 3. roller beam and in (b) the transportation system acting on plate (before 1st side butt welding (SAW).

(a) (b)

Figure 3.12 - Transportation system.

- Turn over unit

For this operation, the welding line facility offers eight independent platforms which lift up the clamped plate by magnetic acting on and steel supports at its bases. The system is composed by eight steel platforms with roller balls and each arm two electric-magnets to fix and support the plates during the turning process, four backwards of the turn and four afterwards. Eight stop blocks placed at the platform feet. All the platforms are thrust by hydraulic cylinder placed underneath them and they are driven by the operator helped for electro-mechanical system available at the main controller panel.

This operation takes around 10 to 17 minutes and it is divided among few steps:

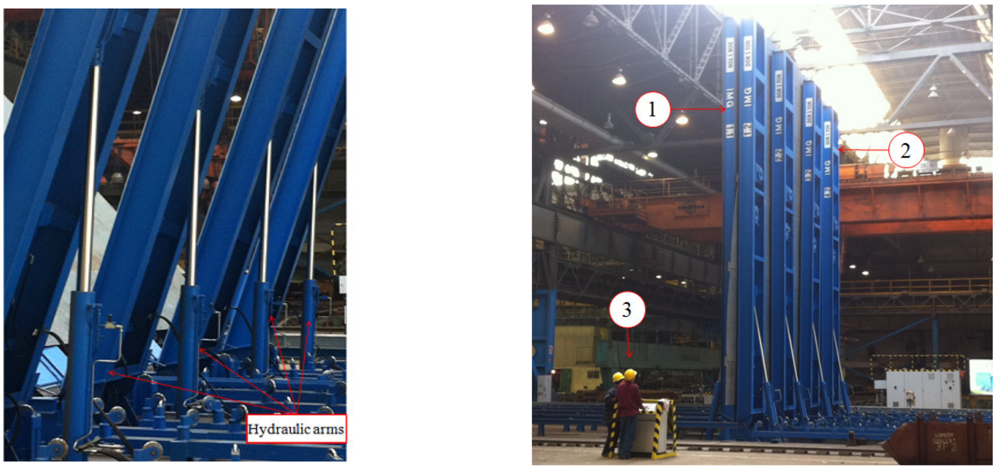
1. Moving of the stop blocks to the turning plate edge
2. Swiveling of the panel with backward-turning platform up to angle of 80°
3. Fix the panel at this position
4. Swiveling of both set of platforms around the turning dead point up to approximately angle of 110°
5. Lowering the panel with the afterwards-turning platform in horizontal position
6. Lowering the backwards-turning platform back in horizontal position

The turning operation are observed and carried out by the operator at the operation panel.

In Figure 3.13 (b) 1. Backwards-turning platforms 2. Stop blocks; 3. Afterwards-turning platforms, and in Figure 3.14 (b) 1. Backwards-turning platforms; 2. Afterwards-turning platforms; 3. Main controller panel.

(a) (b)

Figure 3.13 - Turn unit working.



(a) (b)

Figure 3.14 - Turn unit – parts.

- 2nd Side butt welding (SAW)

Once the panel, with the first side welded is turned upside down, the coming operation becomes expected. Similarly what is done to the 1st side, the 2nd side butt welding needs some preparation to perform it as well. However other facilities available at the 1st side work station, which always have been used at the first operation, are not present at the second workstation, therefore are not necessary at the second side. It means that to perform the second side butt welding using SAW, the panel does not need to be stuck by the magnetic bed neither the copper bar needs to be used in that case.

Before start the second SAW, the worker must drives the welding carriage along the tracks beside the welding line to the 2nd side welding workstation. He must also use a seam tracking system (Figure 3.15) to make the proper alignment of the weld head. After that every welding parameter described at the Appendix A1, imperatively are checked and set up on the welding gantry to perform the work.

In overall, this process usually is faster than the 1st operation. The reason why is because at the 2nd operation such facilities are not used, as mentioned before. Generally 2nd side butt welding takes in between 9 to 14 minutes. It depends on how wide the plate is as well as the 1st side butt welding.

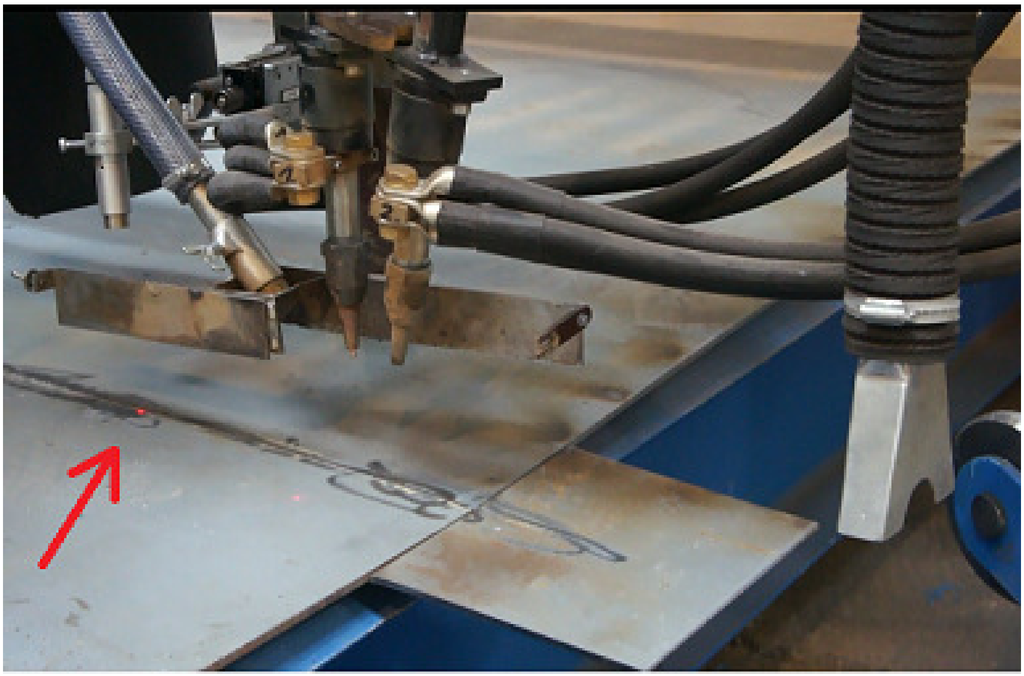
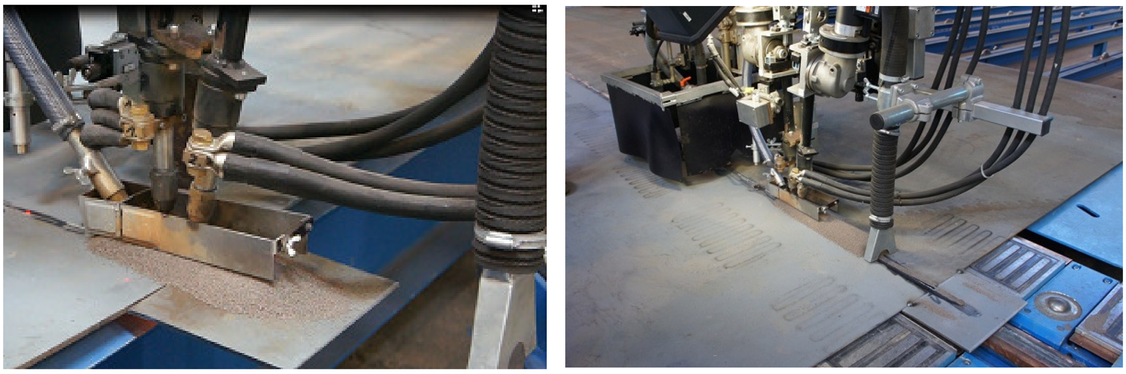


Figure 3.15 - SAW at 2nd side.



(a) (b)

Figure 3.16 - Difference between first and second side butt welding.

In Figure 3.16(a) Beginning of the SAW at second side (without magnetic bed neither cooper bar) and in (b) SAW at first side (is possible to see the magnetic bed and cooper bar on this operation).

After finish the operation, the plate should be cleaned by the operator due to slag from the SAW.

Summarizing, this beginning of the process at welding line is stratified in term of time in Figure 3.17, considering a panel 5-mm-thick, 12-mm-wide ad with 5 steel plates:

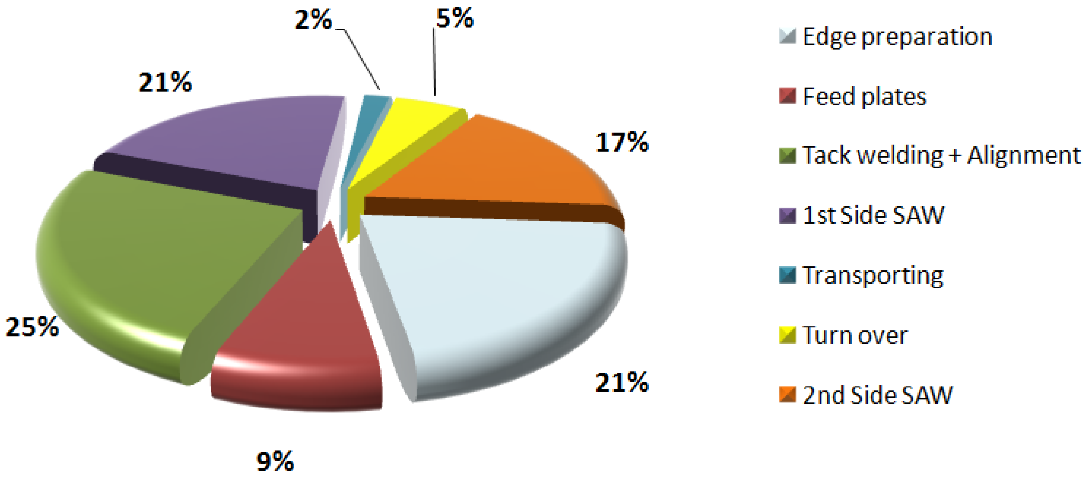


Figure 3.17 - Welding process (in terms of time).

Apart from: the time wasted waiting for crane availability as well as the time to fix the large deformation on the plate edge, the time to replace the raw material and the period for rest of the workers, these operations have an overall time approximately of 5 hours.

3.3.2 Measurement

After understand the work flow, step by step how the process really does work, what are the equipment and worker involved on and which problem should be treated, some strategies and action plan were arranged in the interest of collecting data to figure out the current situation of the deformation after the butt welding using SAW as well as the results which would come from the different condition used for welding parameter and pressure for cooper bar and magnetic at the 1st side welding, according to the Appendix A1.

First of all, the need to improve the welding process in issues related to deformation of ship panel was kept in mind. From this point of view all of the departments which were considered to take part in this experiment have been invited for interacting and suggesting about this problem.

Those departments involved were:

- Production: Welding – due to the fact that the problem is running out at the work shop, with the operator and work stations;
- Metrology: Measurement – to detect such deformation on the steel panel after welding, is necessary to measure directly that. Therefore some knowledge about linear

measurement in addition to the equipments available at shipyard should be evaluated before to start the experiment, to check how the measurement could be done.

- Project (Engineering): Welding – to define condition, similarities and parameter of welding for steel plates, some specialist work force is attainable at shipyard to discuss and help out.

Consecutive of the choice of the departments which should be aware about the experiment, some periodically meetings were carried out by the researcher under supervising of the general director of the shipyard. Those meeting were defined to discuss, to give a frequent feedback about the progress of the experiment additionally the drawbacks which the researcher has found and then to suggest action for solving such issues related to.

During these meeting, some important characteristics were defined such as:

- the kind of experiment which should be performed;
- concerning the proposed experiments, the expected result;
- identification of the panel;
- panel measurement;
- frequency of this measurement.

For each one, the team found a reasonable solution described below:

- Experiment: the theme has been proposed due to some deformation after the butt welding using SAW on the ship panel, as mentioned earlier. For that reason, a proper work aiming to reduce such deformation on the panel has been developed, however only to feel like reducing deformation or put the problems apart from the work shop is not an easy neither a theoretical task. In this case, the researcher really needed to hands on. Hence, the main idea to approach the problem is described at the Figure 3.18:

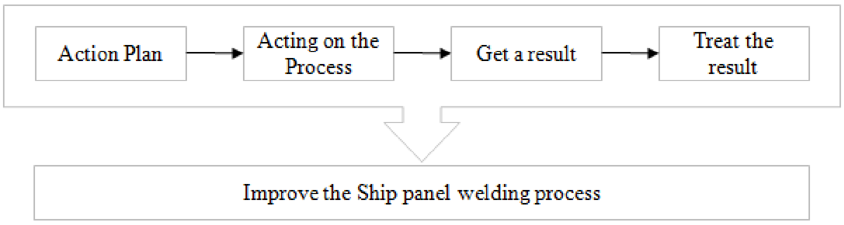
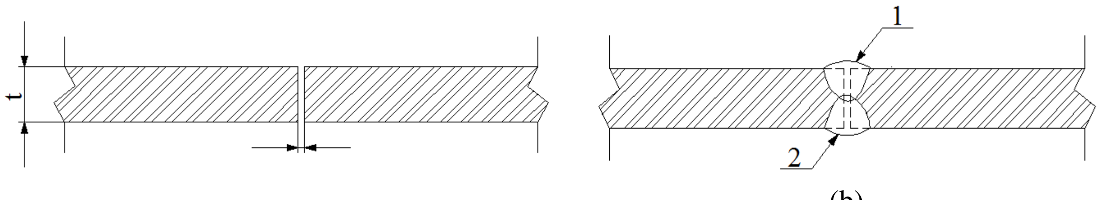


Figure 3.18 - Main idea to approach the problem.

As defined in the section Definition of the Problem, the issue occurs at the work shop and before acting in the workshop some remarks should be taken into account such as: despite of the fact that the production is “producing” the problem, it must not be disturbed or interrupted by the experiment and all of the ideas must be under consent of the team.

From this, the team proposed to perform a design of experiment (DoE) due to the tight time to perform the work at the shipyard and due to the expectation to provide some experience to the researcher in the shipbuilding activities as well as the reasonable results to the shipyard.

Firstly, the conditions for welding process were considered by the welding project department. Some remarks should be assisted on the junction, as described in Figure 3.19 (a) Detail showing the necessary gap between the plate and in (b) Plate cross-section showing the welding penetration on the plates after first and second butt welding.



(a)

(b)

Figure 3.19 - Details on the work piece.

Table 3.2 - Set of parameter encountered before the experiment.

Side	Wire diameter	Current	Voltage	Speed	Heat Input (Calculated)	Magnetics Pressure	Copper bar Pressure
	[mm]	[A]	[V]	[cm/min]	[kJ/cm]	[bar]	[bar]
1	1.2	280	31.4	85	4.9	± 0.9	± 0.4
2	4.0	450	33	90	8.9	-	-

All of the technical characteristics should be respected daily for the workers concerning the welding aspects.

The welding team from the shipyard is composed for the main welder and his partner. They are in charge of all of welding issues in the company from the current process to new project like new welding facilities even training of the workforce. They were in charge to prepare three scenarios which were used during the experiment. These scenarios are concerning the plate 5-mm-thick and the main idea is to have, as a result, variation of the heat input. This heat input which can be associated to the weld energy spent during the weldment itself, according to Lukkari and Vähäkainu (2003)can be described as:

$$Welding\ Energy = \frac{Welding\ Current \times Arc\ Voltage}{Welding\ Speed} \tag{1}$$

According to Funderburk (1999) the heat input is reached as following the relation between the power (in this case current and voltage) per velocity of the heat source, the following equation characterizes such relation:

$$Q = \frac{C \times V \times 60}{S \times 1000} \tag{2}$$

Where:

Q: Heat input [kJ/cm]

C: Current [A]

V: Voltage [V]

S: Speed [cm/min]

Both of them talk about the same phenomenon, the heat input. However the heat input might be different from one type of welding process to another and because of this one factor mentioned by Lukkari and Vähäkainu (2003) is considered in Eq. 2 to distinguish the heat input amongst the welding process - the efficiency factor (k).

In Table 3.3, some examples of Efficiency factor k for different welding process.

Table 3.3 - Efficiency factor k according to Lukkari and Vähäkainu (2003).

Efficiency Factor	Welding Process		
	SAW	MIG	MAG
k	1.0	0.8	0.8

However, the same factor can vary as declared by Vanli and Michaleris (2001) that assume efficiency factor k may be taken according to the Table 3.4:

Table 3.4 - Efficiency factor k according to Vanli and Michaleris (2001).

Efficiency Factor	Welding Process		
	SAW	MIG	MAG
k	0.9	0.75	0.75

This way, for this case the efficiency factor k was assumed as 0.9 for SAW, similarly k equal 0.75 MIG/MAG and MMA and they took part in the welding energy relation for heat input calculation.

As a result, the Eq. 2 becomes:

$$Q = \left(\frac{C \times V \times 60}{S \times 1000}\right) \times k \tag{3}$$

Where:

k: Efficiency factor [%]

Based on the shipyard methodology to define welding parameter, on its historic and reliable data acquired trough experimentally and theoretical background, the engineering department provided the following combination of parameter for welding current (A), voltage (V) and heat speed (cm/min) and then all of the condition for heat input (kJ/cm) have been assessed for that experiment.

Table 3.5 - Set of parameters: Welding.

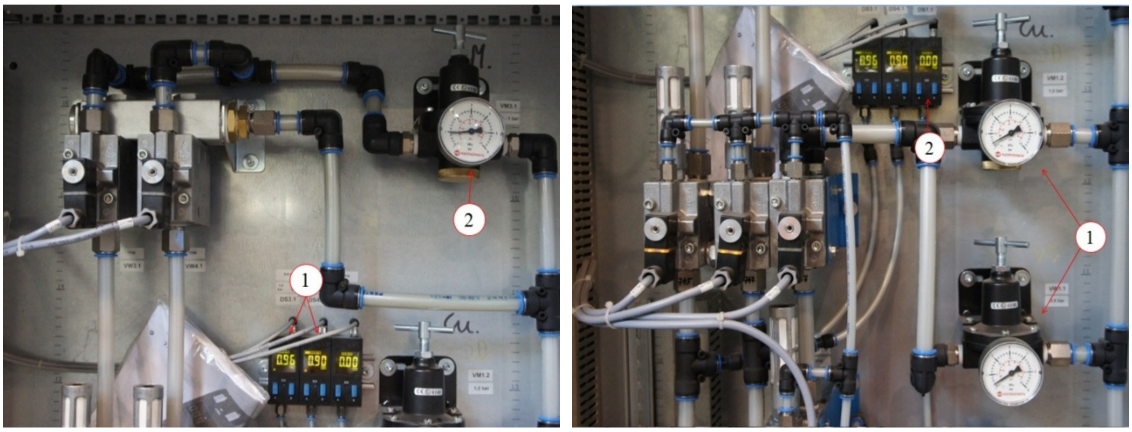
Scenario	Panel Side	Wire diameter [mm]	Method	Current [A]	Voltage [V]	Speed [cm/min]	Heat Input (Calculated) [kJ/cm]	Type of current
1	1	4.0	SAW	400	33	65	10.9	DC+
	2	4.0	SAW	430	34	80	9.9	DC+
2	1	4.0	SAW	410	33	70	10.4	AC
	2	4.0	SAW	420	34	80	9.6	DC+
3	1	4.0	SAW	400	33	60	11.9	AC
	2	4.0	SAW	440	34	80	9.6	DC+

With the welding parameter at hand, another set of parameter remained incomplete. To be able to launch the experiment in the workshop, all of the parameter should be achievable for all of the involved people.

At this point, some contact with the manufacturer of the welding gantry was essential to define a feasible set of pressure for the copper bar and the magnetic, once their influence in the result from the welding process have been considered relevant by the team.

Primarily, the pneumatic system has been studied and its use has been demonstrated by the manufacturer, and it includes: how to operate the air regulator and which components should be taken into account as long as the equipment is working. A brief explanation about the air input and output as well as the manometer in charge of the pressure for each element in the system was carried out by the manufacturer during their technical visit at the shipyards due to maintenance purpose.

The connectivity between the pneumatic panel is ready willing and able at the controller panel alongside of the welding line. This panel is at operator disposal however it is limited just to switch on or switch off the pressures when it is necessary. Changes of any pressure in the system are not allowed by the operator. Specific recommendation from the manufacturer for caring about the changing pressures of magnetic and/or copper bar aim avoiding problem related to overpressure or weak pressure during the welding therefore the access to the pneumatic panel is limited.



(a) (b)

Figure 3.20 - Pneumatic panel.

In Figure 3.20 (a) 1. digital screens for Magnetic pressure and 2. manometer in charge of Magnetic pressure (both beds). Figure 3.20 (b) 1. manometers in charge of Copper bar pressure 2. digital screen for Copper bar pressure.

Once that the pneumatic panel is not a enigma anymore, further discussion about the limit of pressure for that experiment was mentioned and dissertates to the manufacturer like a sort of consulting. As a result, some suggestions were given however some consideration were taken into consideration, such as:

- be careful in how much pressure the system is supposed to bear;
- pay attention at the equipment like manometer, regulator and so on;
- resolution or limitation about the equipment;
- be sure about those changes and write down the variation;
- check the system before start the production.

The limits of the pneumatic system were respected once the amount pressure used was considered to be less than the half of the manometer capacity i.e. the manometer in charge of the pressure for magnetic and for the copper bar. In that way, according to the manufacturer recommendation, the range of variation of the pressure for magnetic and for the copper bar was defined and can be exposed in Table 3.6.

Table 3.6 - Set of parameter: Pressure.

	Equipment			Manufacturer		Experiment		
	Min	Max	Resolution	Min	Max	Min	Aver	Max
Unit	[bar]							
Magnetics	0.0	6.0	0.2	1.0	2.5	1.0	1.4 ~ 1.6	2.0
Copper Bar	0.0	6.0	0.2	0.3	0.6	0.34 ~ 0.36	0.40	0.44 ~ 0.46

As contemplated during the project by the manufacturer, these equipments of pressure which belong to the welding gantry facilities if respecting their pressure limits they can work without any problem. However that analysis carried out was important to understand the overall functioning of the pneumatic system linked to the welding gantry.

Heretofore, all of the factors judged important and/or relevant for the process or at least those ones which might make influence on the final geometry of the panel were considered nevertheless when the experiment starts, which kind of outcome can be expected, or which kind of measurement or consideration can be done in the end, these issue must be treated carefully.

After the numeric consideration to define the parameter for welding and pressure values, some knowledge from the metrology department to answer the question that erstwhile came up to the mind. Hence, basically some methods to measure the deformation or the output from the experiment should be settling down and they were defined experimentally as shown at the Figure 3.21 and Figure 3.24.

The first idea was take the dimension between to peaks, especially on the top of the weld seam, to the bottom, usually in the center of the plate i.e. between two weld seams. Those measurements would be taken in three different positions along the plate, in both plate edges and in the middle plate transversally to the weld seam, according to the sketch shown in Figure 3.21. Such idea was considered and some trials to validate the method were carried out. In detail, in Figure 3.22 (a) 1. ruler to measure, 2. one person to support the ruler and 3. one person to support the string. Figure 3.22 (b) result of the measurement.

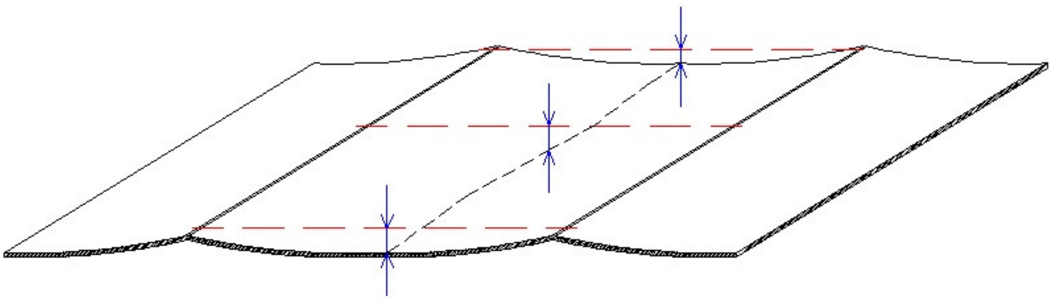
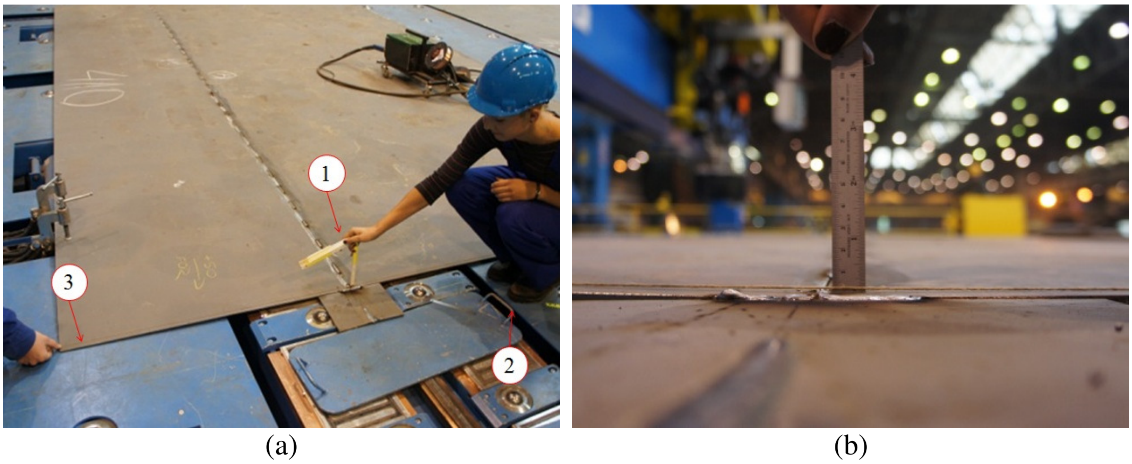


Figure 3.21 - First idea: local of measurement on the steel panel.



(a) (b)

Figure 3.22 - First idea: panel measurement.

Although some results have been provided by this methodology, its execution was not well accepted. Aside from the fact to be necessary at least three people to manage it, the string and ruler disposed like that implies many source of error during the measurement such as:

- the measurement result should be read for a person almost laid down on the floor or on the panel (depend on where the measure is going to be taken) due to the limitations of the view field;
- the parallax error would be any time present during the measurement;
- with this configuration wouldn't be possible to take symmetric measures for both side welding (1st and 2nd). Practically the number of measurement on one side should be equal to the total of measurement done on the other side.

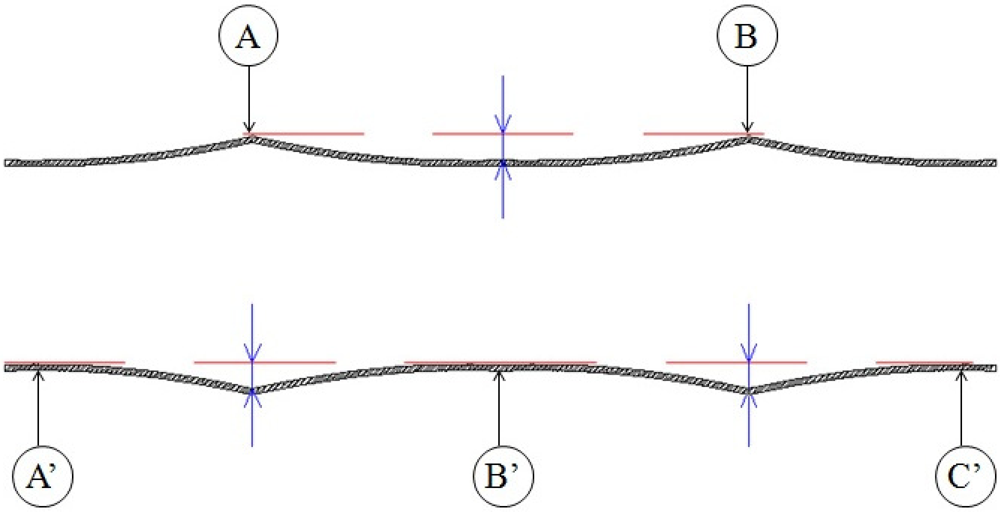


Figure 3.23 - First idea: Drawbacks of panel measurement.

Because of these reasons, the measurement needed to be modified and improved and then another approach has been presented.

Using a theodolite and an auto-supported ruler, only one person was needed to manage the entire measurement process all by himself.

The equipment used consists on the adjustable wooden tripod coupled to the independent lens through the set of screw-nut fixation. For the measurement some characteristics and cares must to be in mind before, during and after the measurement by the person who is in charge, such as:

Before measurement:

- area to settle down the equipment must be flat, without slope or inclined planes;
- the equipment should be settled down in direction of the middle plate;
- the local of the measurement should be clear enough to read the ruler during the operation.

During the measurement:

- level of the measurement equipment assembled should be checked regularly using the bubble level attainable in the equipment;
- the equipment must be untouchable during the operation;
- in case of any disturbance, the equipment must be rearranged again, all the points measured should be discarded and the operation should be restarted;
- throughout the entire panel, the ruler must be positioned correctly fairly enough to the lens in order to avoid parallax error;
- the panel should be in the rest condition, without vibration.

After measurement:

- All the equipment should be carefully disassembled and packed.

Following this advices from the metrology department, some trials were carried out in order to check the performance of this methodology of measurement at the workshop during the experiments. In Figure 3.24is possible to verify all the points measured using the second idea f measurement and in Figure 3.25 (a) proposed condition at the workshop. 1. set of equipment assembled and 2. ruler on the panel.

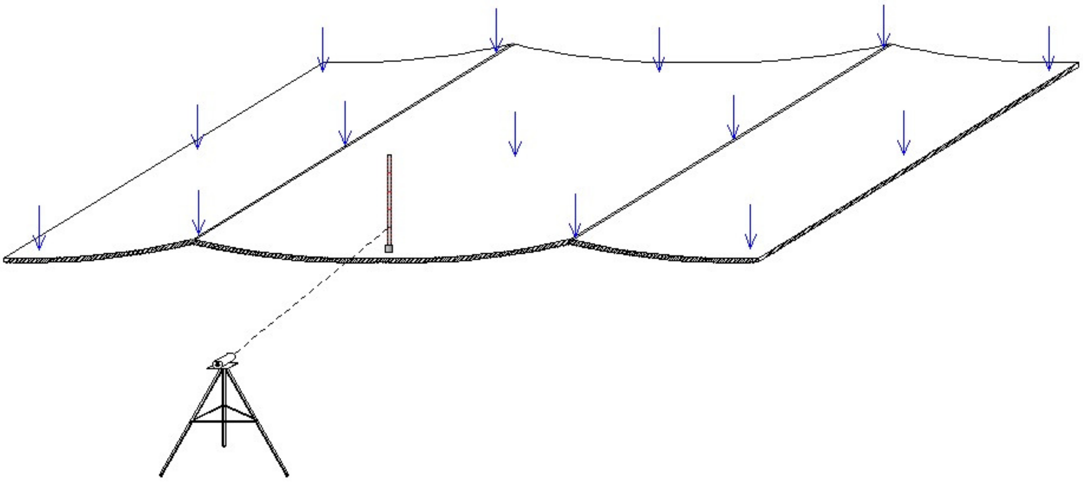


Figure 3.24 - Second idea: local of measurement on the steel panel.

(a)

(b)

Figure 3.25 - Second idea: panel measurement.

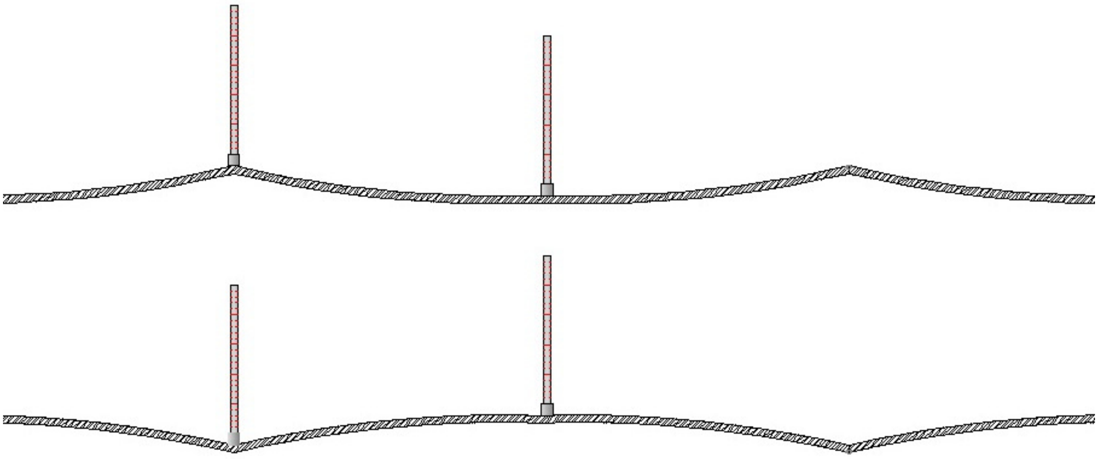


Figure 3.26 - Second idea: symmetric measurement in both sides is possible.

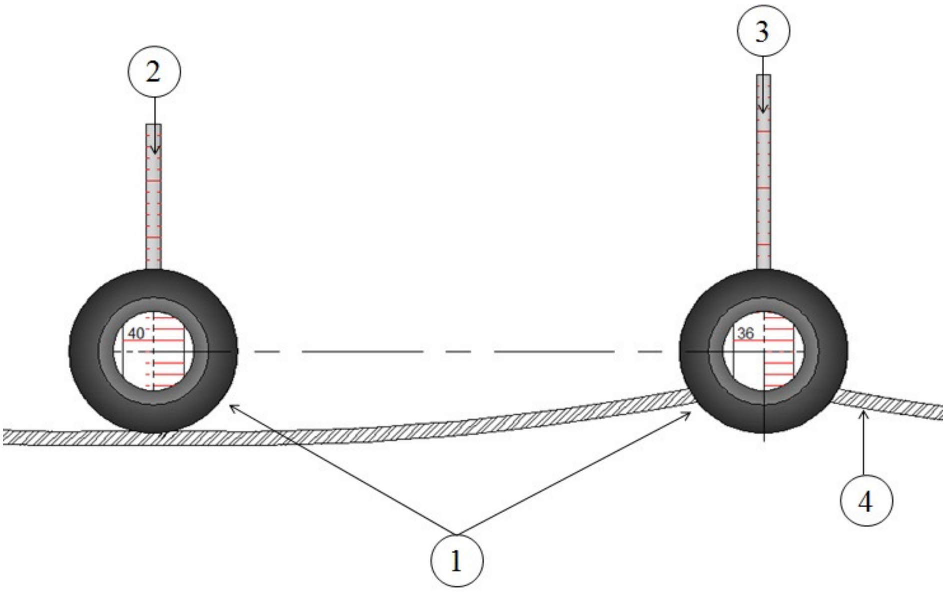


Figure 3.27 - Second idea: view from the equipment lens.

In Figure 3.27 1. equipment lens at the same height, 2. ruler at lower part of the panel, 3. ruler on the higher part and 3. Steel panel.

Table 3.7 - Information of the equipment.

Item	Manufacturer	Characteristics	Model
Lens	Topcon	Magnification 24X	AT-G6
Tripod	-	1 mm high	-
Ruler	-	600 / 1 mm	-

Thereafter analyze all the characteristics of the second method using the theodolite and lens, some other issues came up to be included to this feasibility analysis of measurement, for instance, how the outcomes could be arranged, once the measurement done is punctual i.e. the experimenter will have several different individual points as a result.

From this methodology, is possible to figure out that the results are not a single output. Many numbers will come as from the first side as from the second one of the panel measured. The methodology adopted provides punctual sight therefore the analysis of the overall panel just may be done after all of the points identified and measured. Comparison among the same point in different point might be carried out aiming to verify possible trends occasioned by the welding procedure or any other significant characteristic.

The quantity of the measured point on each panel depend on the number of the plates welded to make the entire panel, for instance, one panel with 3 plates welded together, is possible to check and measure 21 different points. As many plates on one panel we have as many measured points will be available to check. According to the scheme shown in Figure 3.28, is possible to verify how the panel was mapped and identified for each trial.

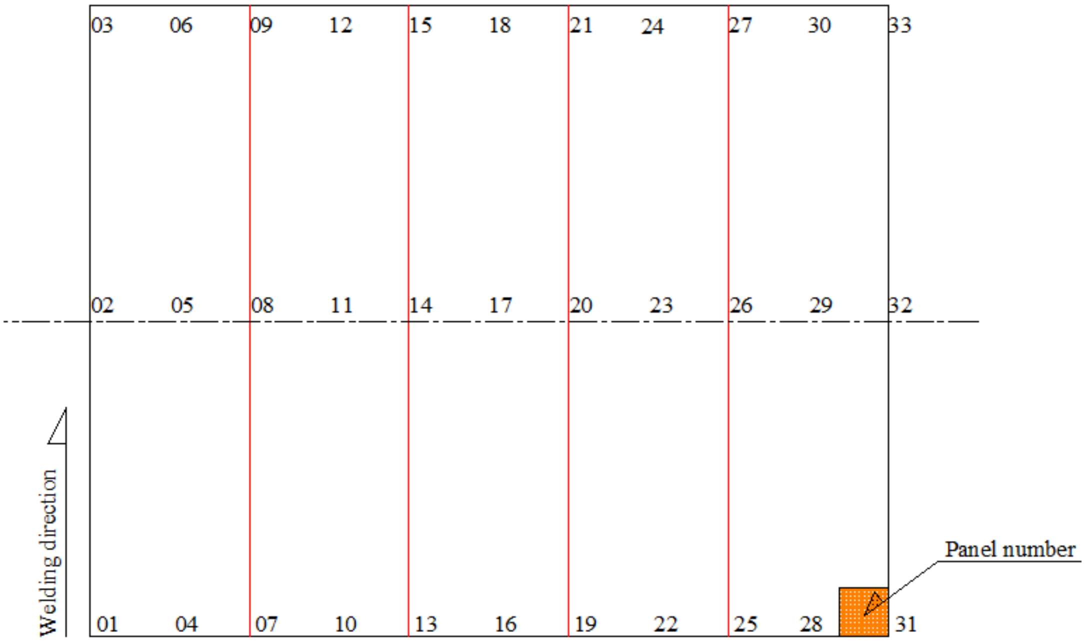


Figure 3.28 - Sketch for a mapped panel.

In Figure 3.28 is shown the sketch of the first side of a 5-plates-panel, as a result 33 measurements. The orange square at corner right bottom symbolizes the place where the panel identification is located.

After this stage, all of the points measured were transcribed to the simple digital spreadsheet and then some considerations were taken into account such as average values among the points, standard deviation as well as the difference between the highest and the lowest point of each side of each panel and like that is possible to realize how big the deformation of the panel is.

Subsequently the methodology to measure, the layout of the panel to be measured and all of the equipment defined to the operation, other important issue arises up when the measurement will be done. Therefore the next step was to define the frequency of those measurements i.e. how many times would be necessary or even possible to measure the panels without disturbing the main production plan or generating delays.

For that reason, considering the production flow explained in Figure 3.6, it was checked whether there are some minutes after 1st side butt welding and before transporting the panel to the turn over unit as well as just after the 2nd side butt welding and before the transportation to the blasting operation. In case of available time, this period is supposed to be used to perform such procedure and take the measurements.

Hence, some measurement has been taken and the average time after SAW has been gotten through direct chronological analysis at the welding line and the outcomes can be shown at Table 3.8.

Table 3.8 - Time after SAW operation at workshop.

Side	Data	Duration (min)
1st Side (Just after 1st side butt welding and before plate transporting)	15/July	78
	20/July	62
	21/July	180
	25/July	85
	26/July	134
	27/July	111
2nd Side (Just after 2nd side butt welding and before plate transporting)	18/July	250
	20/July	240
	22/July	180
	25/July	240
	26/July	240
	27/July	240

After time collection, those results must be compared to the time necessary to measure the entire side panel. However that measurement time can be seen in overall as directly proportional with the panel size, subsequently this measurement time was taken into consideration on the acceptance to measure the panel at the welding production.

This appraisal around the time needed to measure the panel includes the duration to set up the equipment at the welding line, positing the ruler at the right location on the panel, stabilize the panel with respect to avoid vibration during the reading, measure the point using the lens and theodolite and finally writing down the results.

The entire procedure has been followed by the metrology department in order to assure the reliability of the data.

It is also important to state as a remark that all of the measurements was carried out by one person all the time, with regard to avoid error of interpretation or misapplication of the equipment moreover the human factor when the data are being collected or even any other influence related to the operator before, during or after of the measurement.

These data about the time of the panel measurement are achievable at the Table 3.9.

Table 3.9 - Time to measure one side of the panel with 4 and 5 plates.

	Data	Quantity of plates	Time (min)
1 Side	29/July	4	38
	09/August	5	45
	10/August	5	49

With this scenario, is possible to perceive that the time needed to measure is much less than the time available at the flow production. However sometimes is possible to have a kind of special demand and this time becomes shorter therefore some arrangement together to the worker must be done. Due to this time available, the option to perform the measurement has been explained in Figure 3.29.

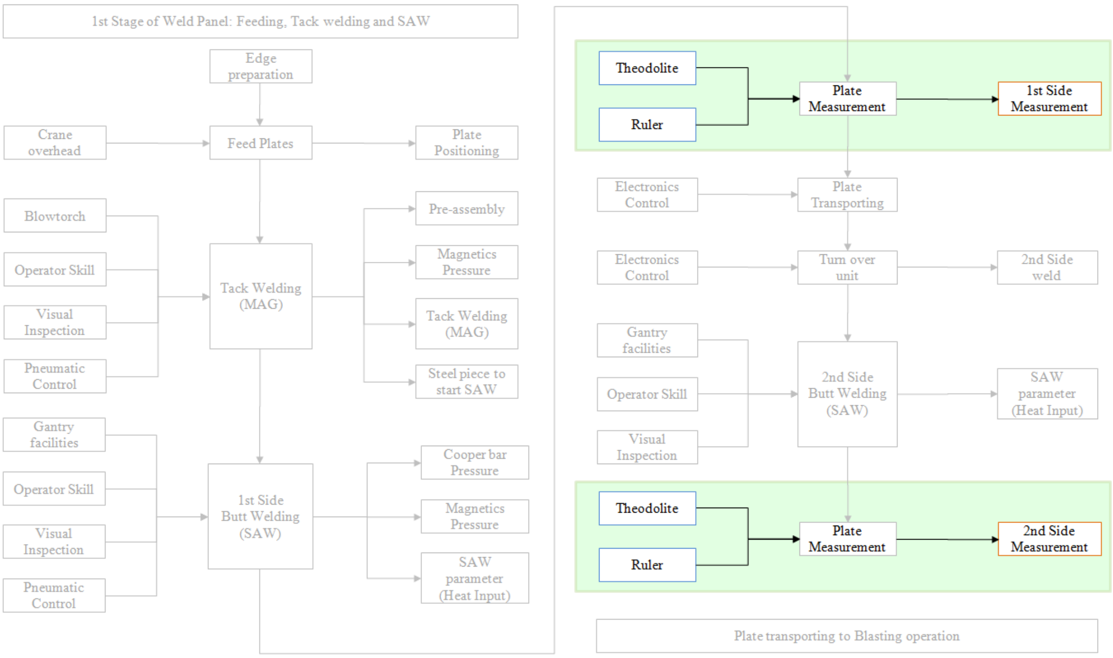


Figure 3.29 - Arrangement to measure the plates.

Some combination and agreement have been done between the workers and then all of the measurements necessary were done without significant hindrances or problems at the workshop.

Like that, one measurement per side of the panel has been defined to be done on each single panel with respect to data acquisition. Square panels with three, four or five steel plate were considered during this experiment.

Summarizing the experiment procedure at workshop, data collection and measurement activities, the Table 3.10 shows the work plan where all the tasks and their responsible and remarks are arranged on, respectively.

Table 3.10 - Work plan for the proposed experiment with its partner.

Item	Activity	Responsible	When?	Frequency
1	Daily work plan management (Production forecast)	Researcher	In the end of the previous day	Everyday
2	Set up of the pressure system, according to the Appendix A1	Researcher	Just before start the welding procedure	1x/trial
3	Set up of the welding parameter, according to the Appendix A1	Operator	Before start the welding procedure	1x/side
4	Welding procedure management (Production performance) 1st Side	Operator / Researcher	During Welding procedure	Everyday
5	1st Side measurement	Researcher	Just after 1st Side butt welding	1x/trial
6	Set up of the welding parameter, according to the Appendix A1	Operator	Before start the welding procedure	1x/side
7	Welding procedure management (Production performance) 2nd Side	Operator / Researcher	During Welding procedure	Everyday
8	2nd Side measurement	Researcher	Just after 2nd Side butt welding	1x/trial

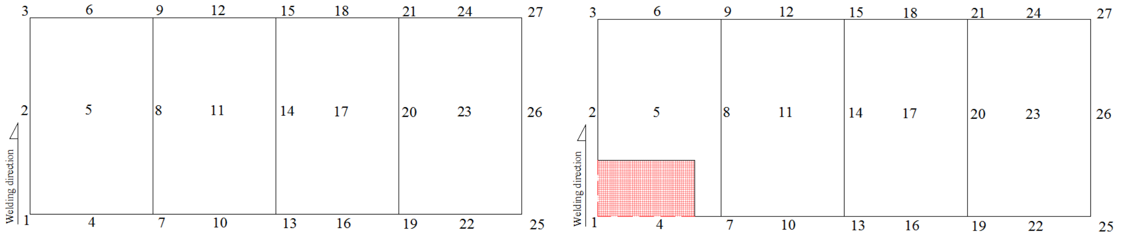
3.4 Data Processing

3.4.1 Data Arrangement

Certainly the theoretical analysis must be carried out in consideration of the data collected during the experiment at workshop. At office, some consideration around the best arrangement about the results obtained have been done day by day just after data collection.

From the measurement method defined in accordance with Figure 3.24, several different types of data arrangement might be reached. Once the measurement is punctual, afterwards each panel has 27 or 33 points measured, depending on the number of plate existent in each panel i.e. if the panel is composed by 5 plates it yields 33 measured points, similarly if the panel has 4 plates in the end it will have 27 measurement.

However, during the data collection not only square panels were measured. A number of panels with cutting were considered and because of this some points which should take part in the data processing could not be achieved. In Figure 3.30 (a) an example of square panel, 4 entire plates and 27 measured points. Similarly in Figure 3.30 (b) a square panel, 3 entire plates and 1 cut plate and only 25 measured points. Points 1 and 4 do not exist.



(a) (b)

Figure 3.30 - Detail on the panels.

Therefore a few primary assumptions were taken into account supposing to get the best condition for data processing in the software and consequently the best configuration for the numerical results. Such remarks are described below:

- due to the fact that the panels are not equals with respect to the number of plates, this analysis will consider only the 4 first plates per panel;
- the measured values for edge panel will not be considered during this evaluation. According to the Figure 3.28, the discarded points will be 1, 2, 3, 25, 26 and 27;
- the area where the measurement was not possible to be performed due to cutting, these point will be discarded;
- only real data from the real panel measured will take place during this analysis;
- the software DX8 will be used to data processing.

From this assumptions some ideas came up to defined the data arrangement in order to get the deformation of each panel. The real condition after measurement is represented through the scheme shown in Figure 3.31.

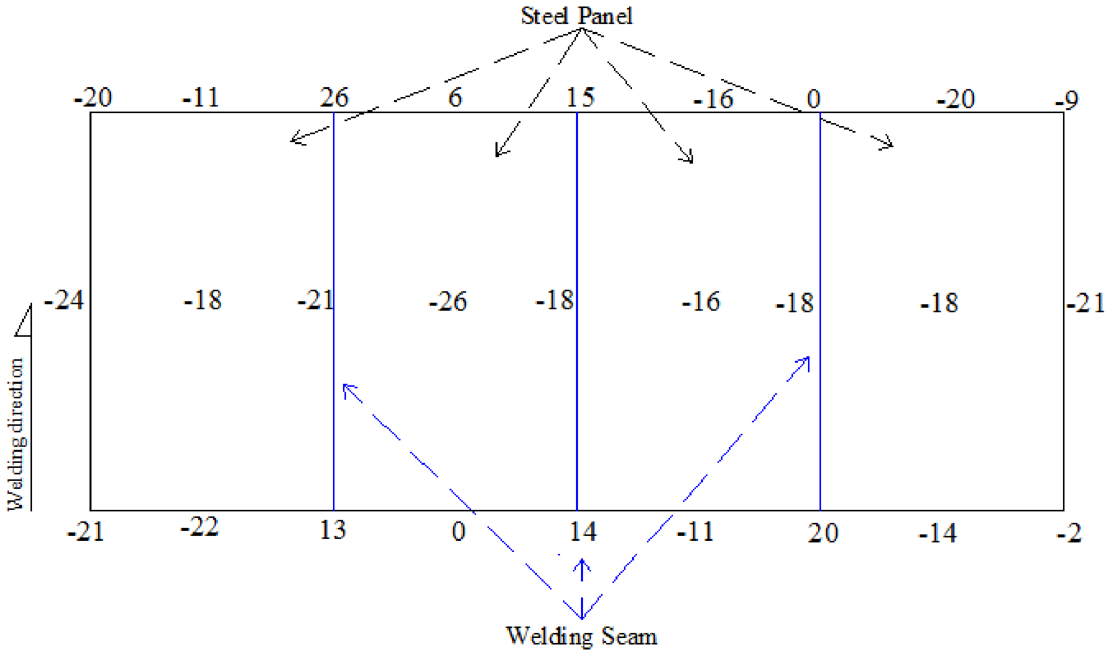


Figure 3.31 - Actual data placed along the panel #20.

The value exposed in the figures above has been gotten after the measurement. It is a simple relation between the minimum and maximum value among all the points to determine the “0” and then all the other points are defined. However such understanding might not give satisfactory result when the data is assessed in the software. For that reason, some data arrangements were tried and their results checked out aiming to get the best condition for numerical prediction (equation results) as well as the statistical concordance.

The first idea for data arrangement was to evaluate the mean value between the related points distributed along the entire panel. However such condition was discarded due to the fact that the each panel has 3 different weld seams connecting its plates, furthermore the deformation should be investigated on each weld seam intending minimize the sources of error over the external factor and even due to initial plate deformation. This way, concentrating the measurement near by the weld seam, such influences from these factors might be mitigated.

Another important remark is that along the panel, 27 measured points have been considered. Like this, on the first plate placed on the left side of the layout scheme shown in Figure 3.28, always is possible to check the points 1 to 9. Nevertheless, as mentioned before the points placed at edge plates will not be taken into evaluation. As a result, on the first plate of the panel there are only points from 4 to 9. Similarly, the others plates have been defined and according to the Table 3.11, for each weld seam the related point are informed.

Table 3.11 - Distribution of the points along the panel respecting the weld seam.

Weld seam	Plates related		Points								
			Starting weld (Edge 1)			Middle Plate			Finishing weld (Edge 2)		
1	1	2	4	7	10	5	8	11	6	9	12
2	2	3	10	13	16	11	14	17	12	15	18
3	3	4	16	19	22	17	20	23	18	21	24

Hence some approaches were examined. One hand, considerations around the mean value of deformation among the points related to the weld seam and on the other hand, the largest value of deformation from the center plate to the weld seam.

From these examinations, the 2 method for data arrangement are explained.

- Option 1 – Mean value arrangement

To illustrate this option (mean values), the Figure 3.32 shows the scheme adopted to get the value. To facilitate the analysis, from now on this arrangement will be mentioned simply as "Option 1".

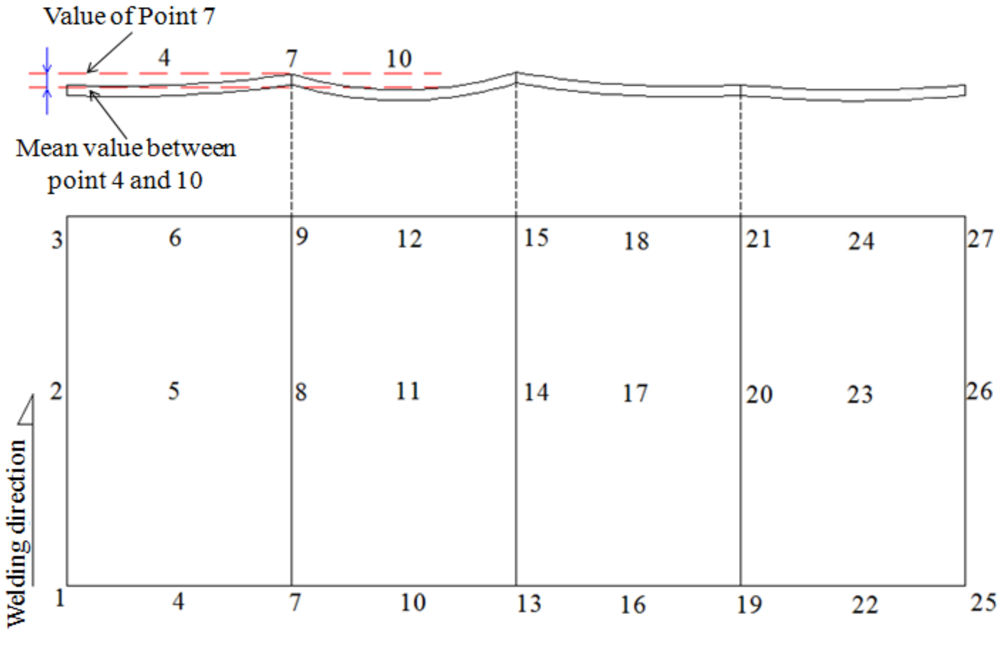


Figure 3.32 - Mean value arrangement: Option 1.

That scheme consists on the mean value between 2 neighbor points (at middle plate) with respect to the point on the weld seam.

$$D_{Op\_1_{i,j}} = \left| \frac{\left(P_{(i+3)+6(j-1)} + P_{(i+9)+6(j-1)}\right)}{2} - P_{(i+6)+6(j-1)} \right| \tag{4}$$

$$D_{Op\_1-seam_j} = Max\left(D_{i,j}\right) \text{with } i \text{ varying from 1 until 3} \tag{5}$$

Where:

j: Characterize the weld seam. A number varying from 1 to 3;

i: The value which determines the position of the deformation along the weld seam. It is a number varying from 1 to 3;

Px: Measured value in mm at the point x, according to Figure 3.28;

x: Index of the point P. It is number which varies from 4 to 24;

$D_{Op\_1_{i,j}}$: is the calculated deformation at weld seam j on the point i;

$D_{Op\_1\text{–}seam_j}$: is the bigger value among the 3 calculated $D_{Op\_1_{i,j}}$ at weld seam j. In other words it will be 1 out of 3 values of deformation considered during the de data processing;

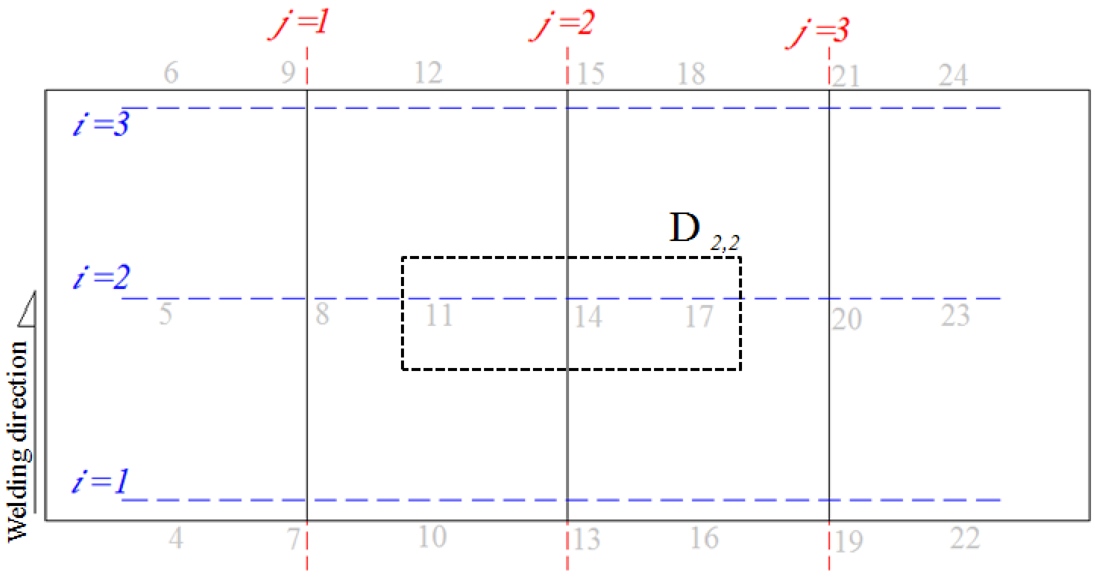


Figure 3.33 - Indexes along the panel.

In Figure 3.33 is easier to verify the condition for positioning of the point in order to calculate the panel deformation. Index used in Eq. 4 and Eq. 5 are exposed and exemplified in Figure 3.33 above. Index i = 1 means the first edge panel; i = 2 middle plate; and finally i = 3 represents the deformation at the second edge panel. At the same way, according to the number, j represents the weld seam under evaluation.

Just to facilitate the understanding, let us illustrate this approach calculating the deformation at middle plate (i = 2) on the second weld seam (j = 2).

$$D_{2,2} = \left| \frac{\left(P_{(2+3)+6(2-1)} + P_{(2+9)+6(2-1)}\right)}{2} - P_{(2+6)+6(2-1)} \right| \quad \rightarrow \quad \boxed{D_{2,2} = \left| \frac{\left(P_{(11)} + P_{(17)}\right)}{2} - P_{(14)} \right|}$$

Therefore, that deformation from this approach involves the point 11, 17 and 14 measured during the experiments as highlighted in Figure 3.33. Furthermore, the deformation considered will be the bigger one among the $D_{Op\_1-seam_2}$.

Adopting this point of view, it is possible to realize that:

- each weld seam has three different values $\left(D_{Op\_1_{i,j}}\right)$(one for each edge and another for the middle plate;
- the biggest value among those 3 measures will be considered as a amplitude on the current weld seam $\left(D_{Op\_1-seam_j}\right)$;
- consequently, each panel yields 3 values for data processing.

- Option 2 – Largest value

Now, illustrating the arrangement taken into account the largest value of deformation around each weld seam is in Figure 3.34. Analogously to the Option 1, this arrangement will be mentioned as "Option 2", just to make the analysis easier.

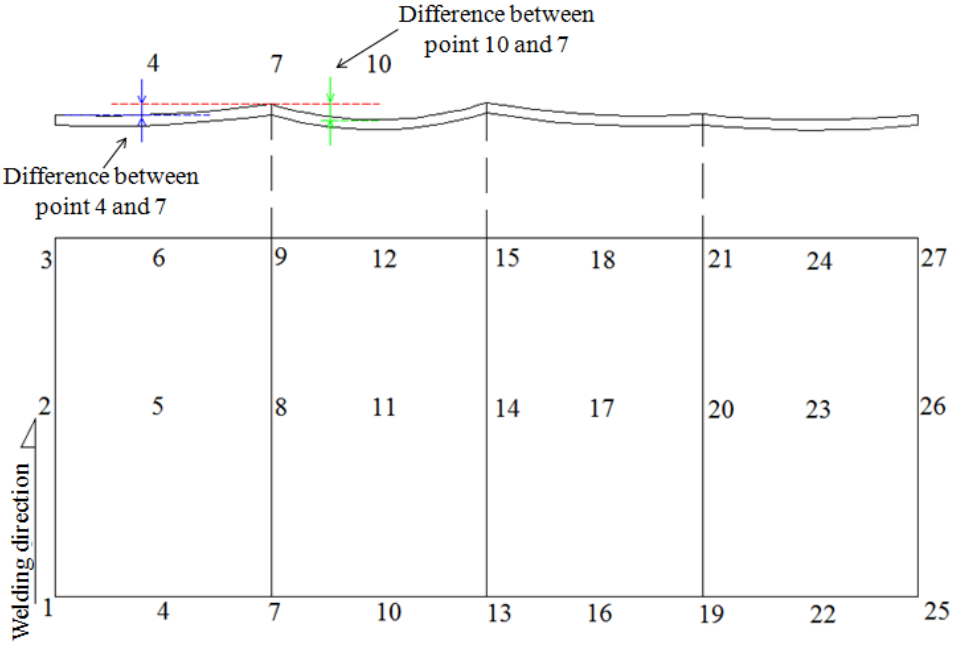


Figure 3.34 - Largest value arrangement: Option 2.

This current scheme works considering the largest value of difference between the neighbor points to the weld seam, individually.

$$D_{Op\_2_{i,j}} = Max\left(\left|P_{(i+3)+6(j-1)} - P_{(i+6)+6(j-1)}\right|, \left|P_{(i+9)+6(j-1)} - P_{(i+6)+6(j-1)}\right|\right) \quad (6)$$

$$D_{Op\_2-seam_j} = \frac{1}{3}\sum_{i=1}^{3}\left(D_{Op\_2_{i,j}}\right) \tag{7}$$

Where:

j: Characterize the weld seam. A number varying from 1 to 3;

i: The value which determines the position of the deformation along the weld seam. It is a number varying from 1 to 3;

Px: Measured value in mm at the point *x*, according to Figure 3.28;

x: Index of the point *P*. It is number which varies from 4 to 24;

$D_{Op\_2_{i,j}}$: is the calculated deformation at weld seam j on the point i;

$D_{Op\_2-seam_j}$: is the average value among the 3 calculated $D_{Op\_2_{i,j}}$ at weld seam j. In other words it will be 1 out of 3 values of deformation considered during the de data processing;

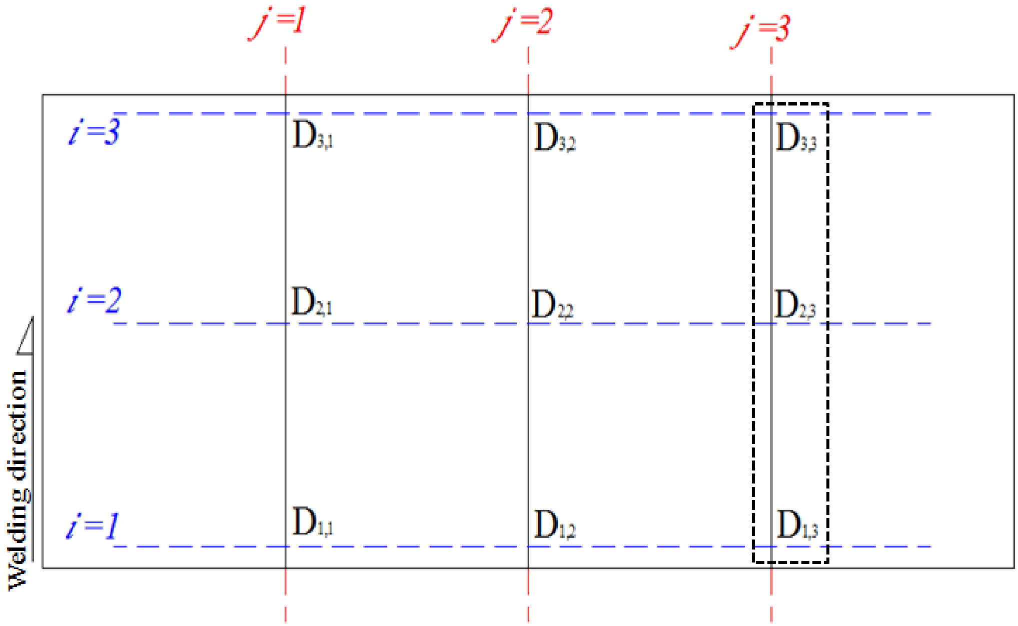


Figure 3.35 - Calculated deformation along the panel.

Similarly to the Option 1, one example can be done to illustrating the method used to calculate the deformation on the panel following the idea explained in Option 2. Let us consider the deformation at the weld seam j = 3. According to the Eq. 6 and Eq. 7, is possible to check that deformation is:

$$D_{Op\_2_{1,3}} = Max\left(\left|P_{(1+3)+6(3-1)} - P_{(1+6)+6(3-1)}\right|, \left|P_{(1+9)+6(3-1)} - P_{(1+6)+6(3-1)}\right|\right)$$

$$\boxed{D_{Op\_2_{1,3}} = Max\left(\left|P_{(16)} - P_{(19)}\right|, \left|P_{(22)} - P_{(19)}\right|\right)}$$

$$D_{Op\_2_{2,3}} = Max\left(\left|P_{(2+3)+6(3-1)} - P_{(2+6)+6(3-1)}\right|, \left|P_{(2+9)+6(3-1)} - P_{(2+6)+6(3-1)}\right|\right)$$

$$\boxed{D_{Op\_2_{1,3}} = Max\left(\left|P_{(17)} - P_{(20)}\right|, \left|P_{(23)} - P_{(20)}\right|\right)}$$

$$D_{Op\_2_{3,3}} = Max\left(\left|P_{(3+3)+6(3-1)} - P_{(3+6)+6(3-1)}\right|, \left|P_{(3+9)+6(3-1)} - P_{(3+6)+6(3-1)}\right|\right)$$

$$\boxed{D_{Op\_2_{1,3}} = Max\left(\left|P_{(18)} - P_{(21)}\right|, \left|P_{(24)} - P_{(21)}\right|\right)}$$

$$D_{Op\_2-seam_3} = \frac{1}{3}\sum_{i=1}^{3}\left(D_{Op\_2_{i,3}}\right)$$

Adopting this methodology, it is also possible to realize some remarks:

- each weld seam has also 3 different values (one for each edge and another for the middle plate;
- the average value among those 3 measures will be considered as a amplitude on the current weld seam;
- consequently, each panel yields 3 values for data processing.

In case of cut plates and missing data, as for the mean value arrangement as for the largest value arrangement the weld seam will not have any value of deformation considered during the data processing.

Once the arrangement is defined, the values for plate deformation used during the data processing are exposed in Table 3.12:

Table 3.12 - Deformation values from 2 data arrangement.

Panel	Heat Input (Q) [kJ/cm]	Copper Bar (CB) [bar]	Magnetics (M) [bar]	Weld Seam	Option 1 [mm]	Option 2 [mm]
01	10.96	0.35	1.0	1	33.0	19.33
				2	39.0	28.67
				3	39.0	22.67
10	10.44	0.35	1.0	1	34.5	26.33
				2	20.5	17.67
11	10.44	0.35	1.5	2	33.0	30.33
				3	36.0	32.00
12	10.44	0.35	2.0	2	33.0	16.00
				3	34.0	24.00
13	10.44	0.4	1.0	1	34.5	29.00
				2	42.0	31.00
				3	37.5	29.67
14	10.44	0.4	1.5	1	33.5	31.33
				2	31.0	29.67
				3	25.0	22.33
15	10.44	0.4	2.0	1	22.5	14.67
				2	18.0	13.67
16	10.44	0.45	1.0	1	35.0	28.33
				2	31.0	23.67
17	10.44	0.45	1.5	1	32.0	28.00
				2	23.5	18.00
				3	28.0	20.33
18	10.44	0.45	2.0	2	16.0	17.00
				3	27.0	13.33
19	11.88	0.35	1.0	1	31.0	23.00
				2	27.5	20.00
				3	17.0	14.67
20	11.88	0.35	1.5	1	28.5	25.67
				2	20.0	21.33
				3	32.5	18.67
21	11.88	0.35	2.0	2	28.0	27.67
				3	24.0	20.00
22	11.88	0.4	1.0	1	14.0	13.33
				2	34.5	19.67
				3	24.0	21.00
23	11.88	0.4	1.5	1	31.0	22.33
				2	32.0	29.33
				3	22.0	21.00
25	11.88	0.45	1.0	1	39.0	32.00
				2	27.0	25.00
				3	20.5	19.00
27	11.88	0.45	2.0	1	27.0	27.33
				2	30.5	28.33
				3	30.0	27.00

In Table 3.12 is possible to check all of the data used to perform the data processing and build the DoE. It is also clear that sequence of number is not complete and the number of welding seam is not regular. Because of this, a number of explanations should be mentioned:

- during the data collection was defined to perform a Design of Experiment intending to have a comprehension about the welding deformation through numerical understanding;
- to perform the DoE, 3 parameters were defined as relevant factors which make influence on the welding deformation and they were: heat input (Q), pressure from the Copper Bar (CB) and pressure from the Magnetics (M);
- each parameter had 3 different levels: minimum, average and maximum. Playing with those 3 parameters and their 3 levels, easily is possible to verify 27 distinct trials i.e. 27 different panels;
- however, due to the tight time perform the experiment as well as the drawbacks present in the shipyard routine, unfortunately only 19 out of 27 trials were able to be accomplished;
- the set of parameter are described in Table 3.13;
- to build the DoE only 17 out of 19 completed trials data have been used. The others 2 trials, their data will be used to compare and to make a partial evaluation of the numerical equations reached through the others data;
- despite of the fact that both side were controlled and measured during the trials (as explained before), only the 1st side butt welding has been considered during this evaluation. It happens due to the fact the deformation is created after the 1st side butt welding, moreover while this stage is used the copper bar and magnetic, as described on the section*Panel Production*.

Table 3.13 - Trials performed in the Shipyard – summarization.

Trial	Parameter Q [kJ/cm]	CB [bar]	M [bar]	Number of welding seam	Trial Status [Ok or NOk]
01	10.96	0.35	1.0	3	Ok
02	10.96	0.35	1.5	-	Not Ok
03	10.96	0.35	2.0	-	Not Ok
04	10.96	0.40	1.0	-	Not Ok
05	10.96	0.40	1.5	-	Not Ok
06	10.96	0.40	2.0	-	Not Ok
07	10.96	0.45	1.0	-	Not Ok
08	10.96	0.45	1.5	-	Not Ok
09	10.96	0.45	2.0	-	Not Ok
10	10.44	0.35	1.0	2	Ok
11	10.44	0.35	1.5	2	Ok
12	10.44	0.35	2.0	2	Ok
13	10.44	0.40	1.0	3	Ok
14	10.44	0.40	1.5	3	Ok
15	10.44	0.40	2.0	2	Ok
16	10.44	0.45	1.0	2	Ok
17	10.44	0.45	1.5	3	Ok
18	10.44	0.45	2.0	2	Ok
19	11.88	0.35	1.0	3	Ok
20	11.88	0.35	1.5	3	Ok
21	11.88	0.35	2.0	2	Ok
22	11.88	0.40	1.0	3	Ok
23	11.88	0.40	1.5	3	Ok
24	11.88	0.40	2.0	3	Ok
25	11.88	0.45	1.0	3	Ok
26	11.88	0.45	1.5	3	Ok
27	11.88	0.45	2.0	3	Ok

In the end there are 50 points available, distributed along the 19 trials. The run 24 and 26, their data will be used for partial confirmation of the DoE. Hence, the DoE will have 44 data as described in Table 3.12.

3.4.2 Software DX8

Intending to aid the analysis, an electronic tool for data processing has been used. The software DX8 is a statistical instrument with provides in-depth analysis of process factors, to perform a consistent DoE, besides its friendly interface.

For this analysis, the methodology chosen is 2-level Factorial. The levels of the factors are in accordance to the Table 3.5 and Table 3.6. These values contemplate the values of maximum and minimum of the 3 factors used during the experiment. Although only maximum and minimum limits have been specified, some intermediate values may be added during the data processing intending to use all the trials mentioned earlier.

Respecting some statistical feature and an interval of confidence of 95%, the results of both data arrangement are exposed at the Table 3.14:

Table 3.14 - Results of the models. Data from software DX8.

Item	Specification	Model (Method)							
		Option 1			Option 2				
		General Analysis							
Standard Deviation – Data	-	6.7			5.6				
Minimum value	-	14.0			13.3				
Maximum value	-	42.0			32.0				
		ANOVA							
Terms of the Model	-	Q	M	Q*M	Q	CB	M	Q*CB	Q*M
P-value – Terms	<0.05	0.17	0.07	0.02	0.91	0.54	0.26	0.04	0.0
P-value – Model	<0.05	0.01			0.0				
Residual Mean Square	-	37.61			22.48				
F value – Model	-	3.93			4.44				
F value – Terms	-	1.93	3.42	5.46	0.01	0.38	1.31	4.28	15.26
Lack of Fit	>0.05	0.34			0.1				
Standard Deviation	-	6.1			4.7				

Comparing the outcomes for these 2 models is possible to verify some important characteristics, such as:

- Terms of the model

Whereas the terms for the model are not defined, nothing can be calculated. According to the data input, the software computes the effects of each term in the results. From this the experimenter may choose those one which make really difference in the outputs. In this current case, on one hand for the Option 2 the terms chosen involve all the parameter considered: Q, CB, M and combination.

Nevertheless, on the other hand the Option 1 found relevance only on Q, M and Q*M. This model does not contemplate the influence of the copper bar.

The choice of the terms is based on the hierarchy system, where the main factors must be included in the model in case of the combination between them shows relevant contribution for the expected results, even if they are not as significant as their combination from statistic point of view.

- Probability value (P-value) of the model

Both arrangement yielded results which assisted the significance probability according to the software outputs. Both models showed figures of p-value less than 0.05. It means the models which have been analyzed have a small probability (less than 5% of chances) to be wrong from the samples used as input data. It might be considered a good result for both models. Although the models are respecting the 95% interval of confidence it is not a guarantee that the models are fully correct.

- Probability value (P-value) of the terms

Similarly, the terms chosen and subscribed as a significant in relation to the effects (deformation) showed reasonable values for p-value < 0.05, with exception of the main factors in both cases. The combination between Q*M in the Option 1 as well as the combination Q*CB and Q*M in the Option 2 are really representative and they are respecting the p-value limits. The terms with p-value bigger than 0.05 may cause some noise for the model, however these 2 models are respecting the hierarchy therefore the main factors are included and they will take part on the prediction of the results.

The software computes the influence of each term over the results. From this, the choice about the terms to compose the model might be done based on the half-normal probability plot, for instance. In this graph, the software places the most important terms on upper-right corner and on the lower-left corner the effects without much relevance or those ones caused by the noise instead of the actual effects. A hint to choose the terms consists on observation of the gap between the effects. In Figure 3.36 and Figure 3.37 is shown the effects of the terms which belong to the model selected of both Options on the Half-Normal Plot provided by the software.

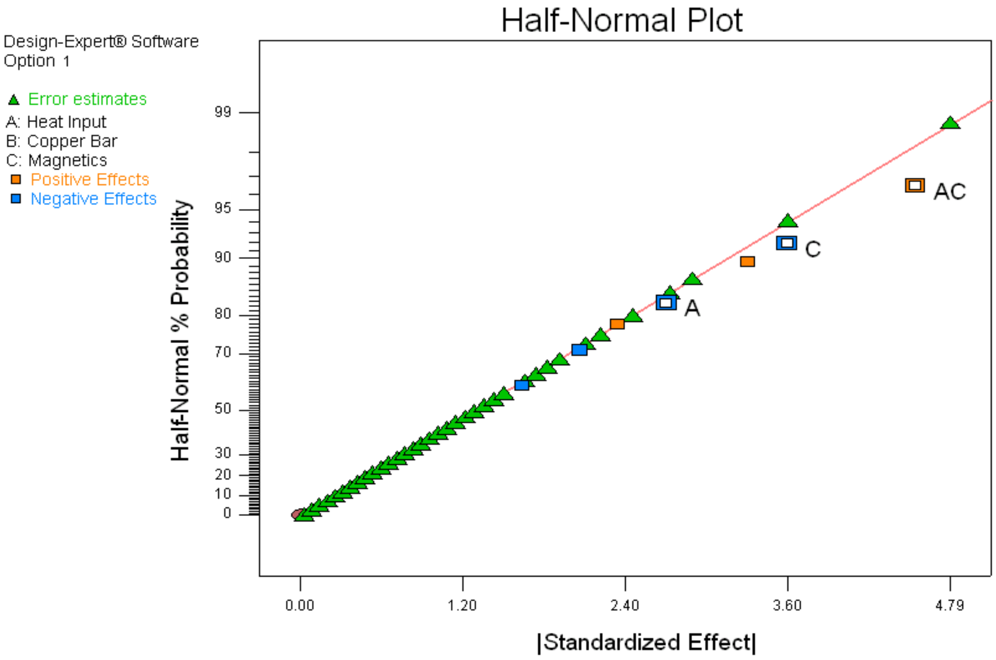


Figure 3.36 - Effect of the selected terms in the Option 1.

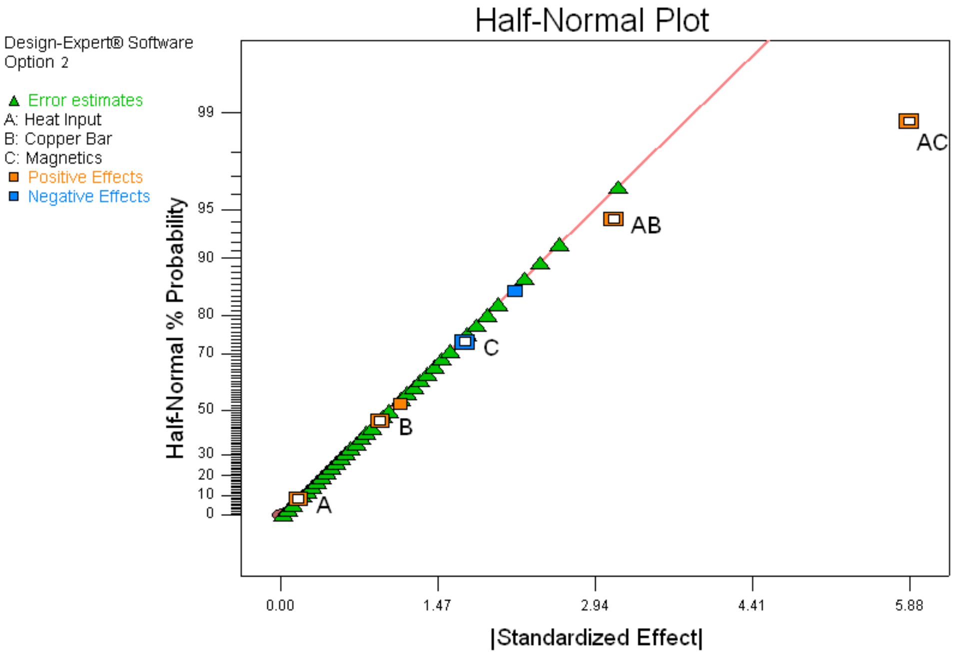


Figure 3.37 - Effect of the selected terms in the Option 2.

- F-value of the model

In both cases the F distribution is satisfactory. As bigger this number as better. From this point of view the Option 2 presents better condition than the Option 1. However, with this condition, these 2 models can explain the variance more than the noise.

- F-value of the terms

Similarly, the most of the terms chosen and subscribed as a significant in relation to the effects (deformation) showed reasonable values for F-value. Nonetheless, the main factors Q and CB in Option 2 have values smaller than 1. It is not a problem once that is recommended that the term presents greater value in this characteristic. Anyhow as figured out in p-value analysis the main factor must be included in the model in order to assist the hierarchy condition.

- Lack of fit

This characteristic evaluates the model suggested with respect to its values. It shows whether the model fits well the data available. It also is computed through a p-value, however its value is expected to be higher than 0.1 becoming the lack of fit not significant to the model. If the result is higher than 0.1 it is not significant and it means that there is a small probability of the pure error be larger, in other words, the model has been fitted.

In the current case, the lack of fit found for the Option 2 is equal 0.1 and for the Option 1 the lack of fit is satisfactory. It would be better larger value for Option 2, even though this value might be considered as a satisfactory.

- Residual

Another important feature which has been evaluated during this work is related to the levels of residuals found in the each model. In Figure 3.38 and Figure 3.39 is possible to check the variation of the residual of each model.

Those values are gotten throughout the difference between the predicted values and the actual value. From these values of residual, the standard deviation is computed. To illustrate the behavior of those models, a limit of ± 3 standard deviations (computed by the residuals) have been used.

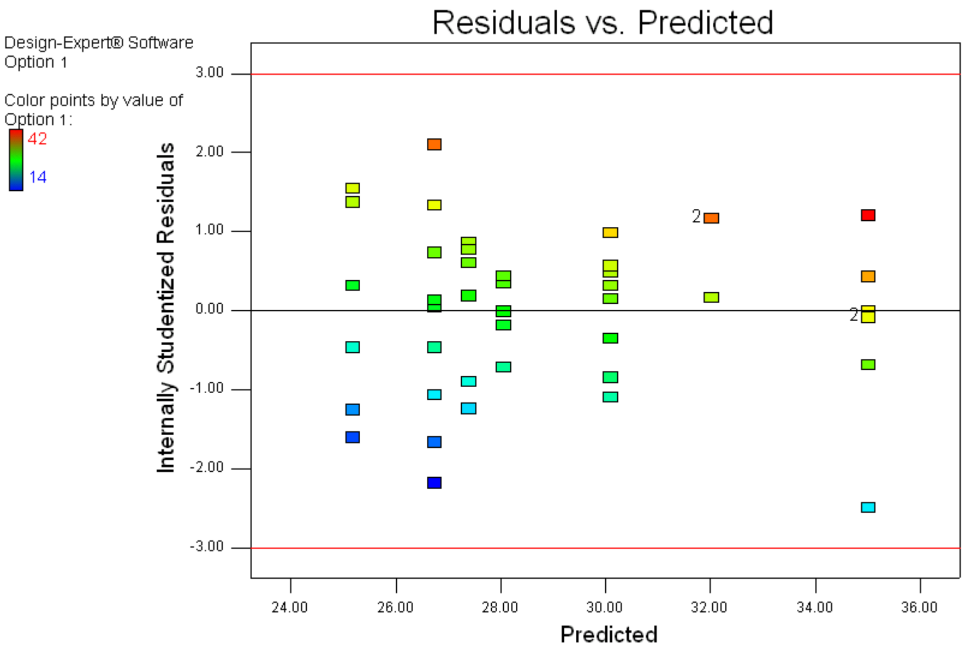


Figure 3.38 - Residuals versus estimated residuals standard deviation: Option 1.

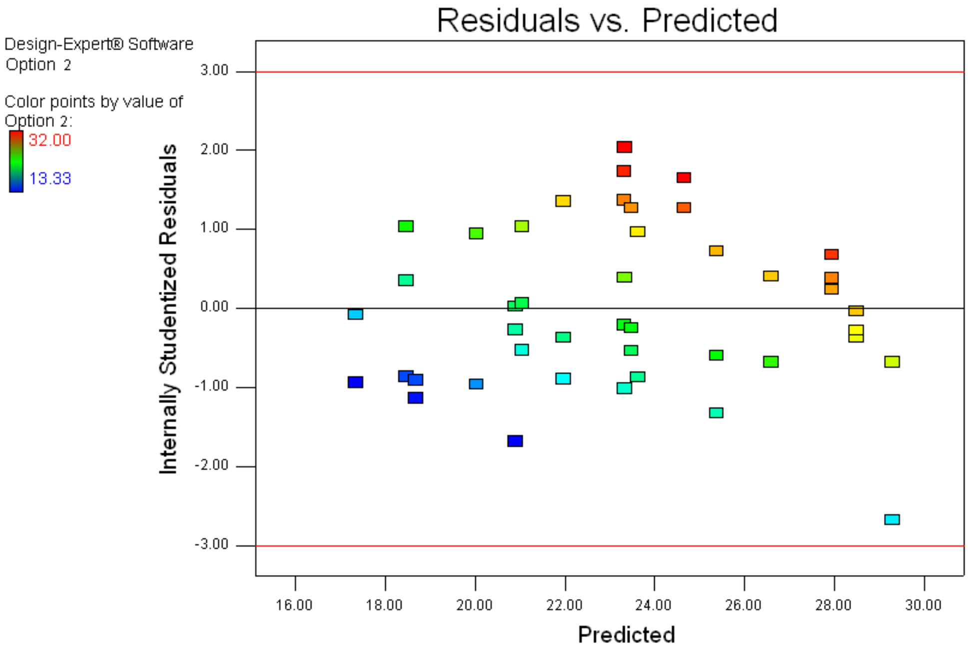


Figure 3.39 - Residuals versus estimated residuals standard deviation: Option 2.

Checking the figures is easy to verify that the two cases all the residuals points calculated are spread in the stipulated limits.

- Residual per factor

Once the residual of the 2 models is assessed in a general view, an evaluation of residual versus each factor is also appropriate. From the Figure 3.40 to the Figure 3.45 such situation has been illustrated and it is shown the comparison between the residual from Option 1 and Option 2 versus the main factors included in the models: Q, CB and M.

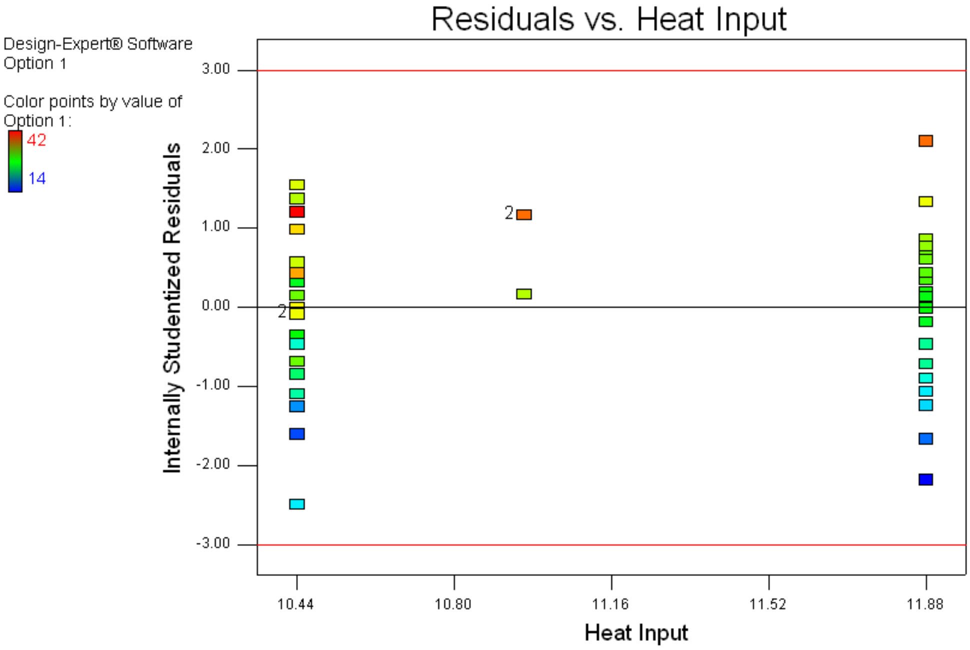


Figure 3.40 - Value of residual versus factor Q. Option 1.

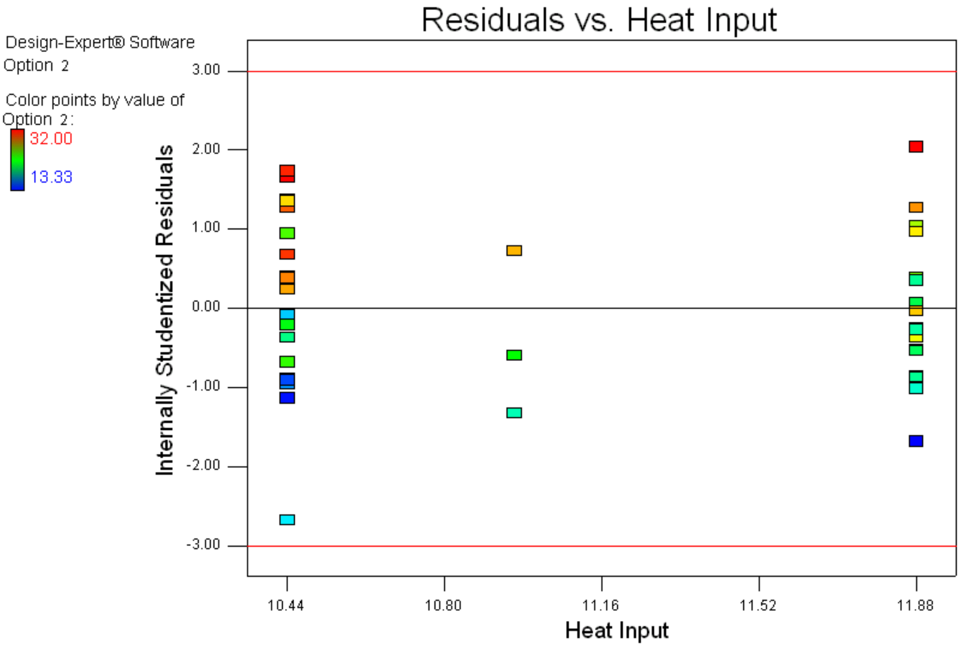


Figure 3.41 - Value of residual versus factor Q. Option 2.

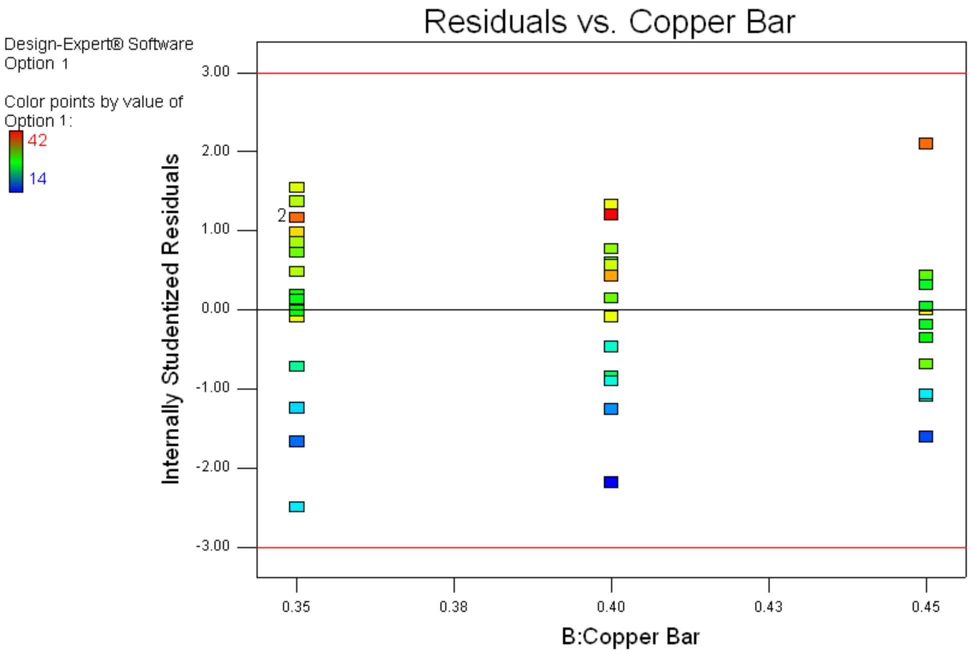


Figure 3.42 - Value of residual versus factor CB. Option 1.

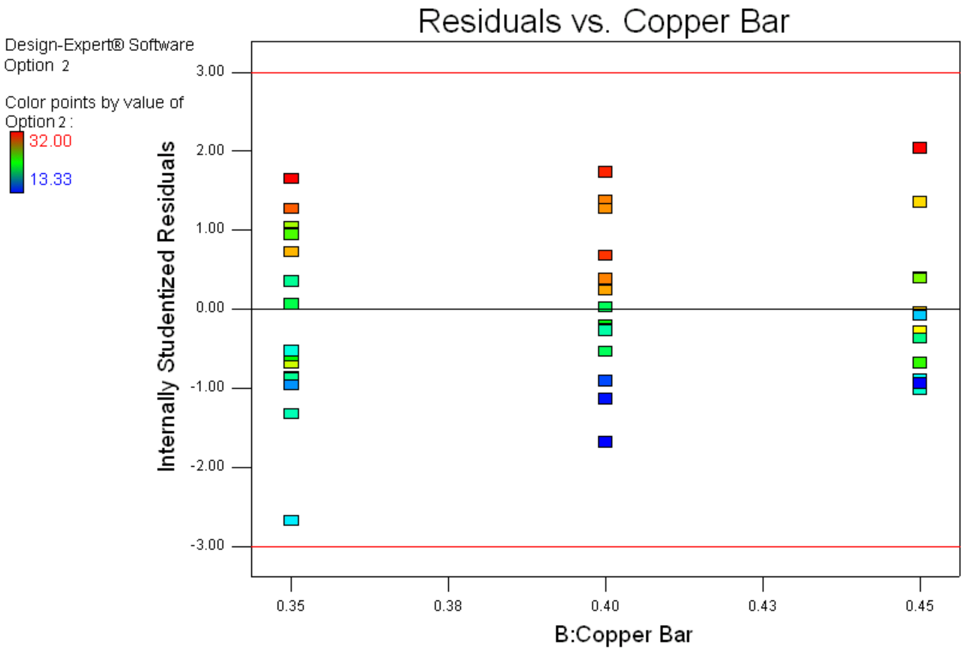


Figure 3.43 - Value of residual versus factor CB. Option 2.

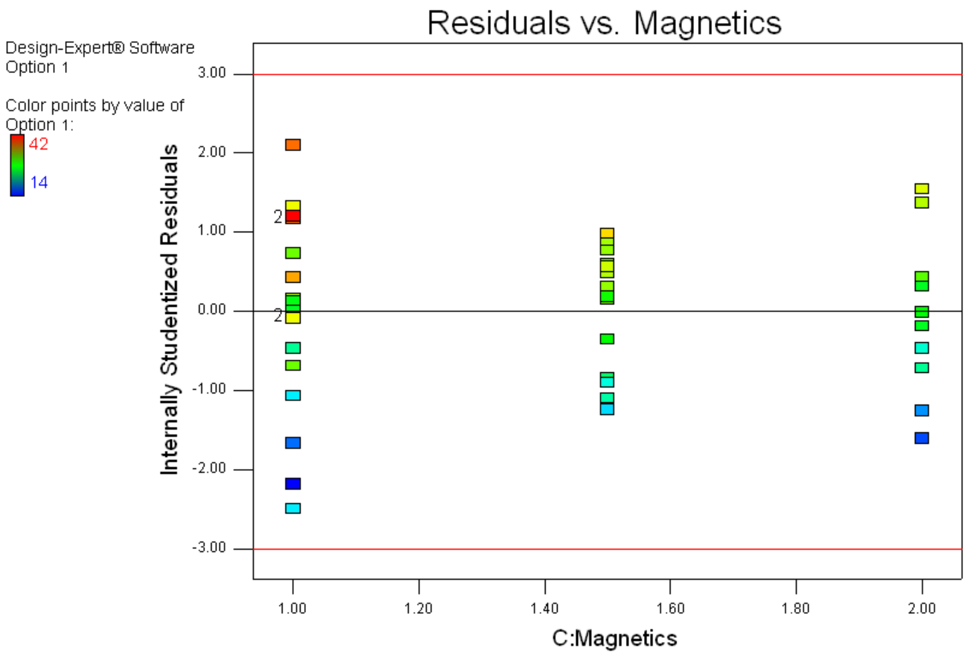


Figure 3.44 - Value of residual versus factor M. Option 1.

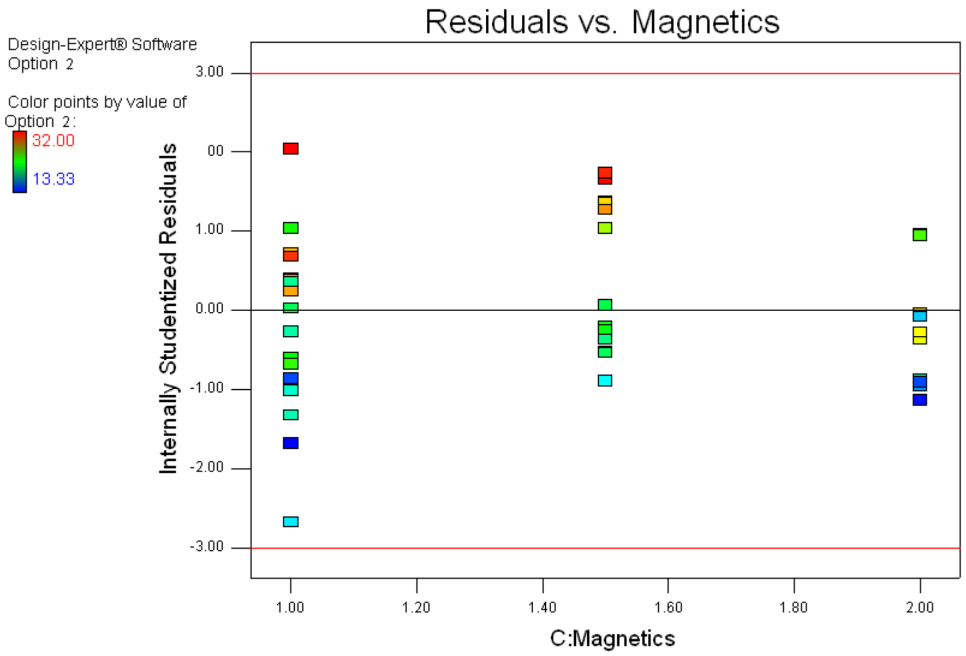


Figure 3.45 - Value of residual versus factor M. Option 2.

Similarly to the scheme presented in Figure 3.38, all of the values are fitted in the stipulated limits.

- Standard Deviation

Finally, the last, but not less important, topic taken into consideration during the analysis in DX8 software is the standard deviation provided by the root square of the residual mean square and it is deeply linked to the experimental error. Small values of difference between predicted and actual values generate small residual and consequently small standard deviation. Therefore a small value is desirable for this topic.

In the prevailing analysis the values found are accepted but the Option 2 has a result slightly better than Option 1.

Summarizing the models, as a result it is possible to verify that both options are portraying the deformation as it really is. However, as explained before, all the parameter might contribute somewhat for the welding deformation and therefore it recommended that all of the factor may be included in the model. The arrangement proposed by the Option 1 does not realize the influence coming from the pressure of the Copper Bar, thereupon the model is regarding only the effects from the Heat Input and pressure of the Magnetics.

On the other hand, the model explained through the Option 2 is relating all the main factors besides some of their combination. It might be acknowledged as a model better than the one described in Option 1, once all of the main factors are interacting to each other.

Other important issue to be mentioned concerns to the sources of error. In the whole procedure described so far, many situations occurred and probably they might make influence on the accuracy of the results provided by the model. Some examples of these situations can be seen in Figure 3.46 and in Figure 3.47 (a) the panel is not settled down on the tracks and in Figure 3.47 (b) an unusual deformation between the weld seams.

(a) (b)

Figure 3.46 - Cutting nearby the weld seam.

(a) (b)

Figure 3.47 - Plate deformation.

The main evaluation of the data using statistical software DX8 has been done. The results about the deformation and accuracy of the model as well as the partial evaluation of the numerical equation using the results from the trails 24 and 26 will take place in the next section Results and Discussion.

4 RESULTS AND DISCUSSION

After some meticulous analysis around the models adopted to describe on the best way the deformation encountered on the ship steel panel in a Polish Shipyard, some figure regarding the accuracy of those models as well as the predicted values presented for them will be shown in this chapter.

The values used to get the prediction equations for the model named as Option 1 and Option 2 are exposed in Table 3.12. Although a few other approaches for data arrangement had been tried, only those 2 were described intending to make the data processing chapter simpler and easier to understand. Therefore, in this current chapter the same condition will be used and only the results for Option 1 and Option 2 will be presented and discussed.

From the data input in the DX8 statistical software, a numerical equation has been yielded as a result. Using these equations is possible to verify the results and then the accuracy of each one provided by the models with respect to the actual value of deformation measured on the steel ship panel in the Polish shipyard.

The numerical equation is presented below:

- Option 1 – Mean value arrangement

$$\begin{aligned} D_{Op_1} = \; & +185.70023 \\ & -13.49115 \cdot Q \\ & -90.68556 \cdot M \\ & +7.74432 \cdot Q \cdot M \end{aligned} \tag{8}$$

- Option 2 – Largest value arrangement

$$\begin{aligned} D_{Op_2} = \; & +422.45083 \\ & -35.87045 \cdot Q \\ & -574.07631 \cdot CB \\ & -113.80114 \cdot M \\ & +52.41132 \cdot Q \cdot CB \\ & +10.01348 \cdot Q \cdot M \end{aligned} \tag{9}$$

Thus, in Table 4.1 is possible to check:

- the values gotten from the arrangement Option 1 and Option 2;
- the predicted value yielded from the Eq. 8 and Eq. 9 for each set of parameter;
- the estimated error found through the residual value.

Table 4.1 - Values of deformation and residual from 2 data arrangement.

Panel	Weld Seam	Option 1			Option 2		
		Actual Value [mm]	Predicted Values [mm]	Residual [mm]	Actual Value [mm]	Predicted Values [mm]	Residual [mm]
01	1	33.0	32.0	-0.97	19.33	25.38	6.05
	2	39.0	32.0	-6.97	28.67	25.38	-3.29
	3	39.0	32.0	-6.97	22.67	25.38	2.71
10	1	34.5	35.0	0.52	26.33	29.29	2.96
	2	20.5	35.0	14.52	17.67	29.29	11.62
11	2	33.0	30.1	-2.9	30.33	24.66	-5.67
	3	36.0	30.1	-5.9	32.00	24.66	-7.34
12	2	33.0	25.2	-7.82	16.00	20.03	4.03
	3	34.0	25.2	-8.82	24.00	20.03	-3.97
13	1	34.5	35.0	0.52	29.00	27.94	-1.06
	2	42.0	35.0	-6.98	31.00	27.94	-3.06
	3	37.5	35.0	-2.48	29.67	27.94	-1.73
14	1	33.5	30.1	-3.4	31.33	23.31	-8.02
	2	31.0	30.1	-0.9	29.67	23.31	-6.36
	3	25.0	30.1	5.1	22.33	23.31	0.98
15	1	22.5	25.2	2.68	14.67	18.68	4.01
	2	18.0	25.2	7.18	13.67	18.68	5.01
16	1	35.0	35.0	0.02	28.33	26.6	-1.73
	2	31.0	35.0	4.02	23.67	26.6	2.93
17	1	32.0	30.1	-1.9	28.00	21.97	-6.03
	2	23.5	30.1	6.6	18.00	21.97	3.97
	3	28.0	30.1	2.1	20.33	21.97	1.64
18	2	16.0	25.2	9.18	17.00	17.34	0.34
	3	27.0	25.2	-1.82	13.33	17.34	4.01
19	1	31.0	26.7	-4.26	23.00	18.47	-4.53
	2	27.5	26.7	-0.76	20.00	18.47	-1.53
	3	17.0	26.7	9.74	14.67	18.47	3.80
20	1	28.5	27.4	-1.1	25.67	21.05	-4.62
	2	20.0	27.4	7.4	21.33	21.05	-0.28
	3	32.5	27.4	-5.1	18.67	21.05	2.38
21	2	28.0	28.1	0.06	27.67	23.63	-4.04
	3	24.0	28.1	4.06	20.00	23.63	3.63
22	1	14.0	26.7	12.74	13.33	20.9	7.57
	2	34.5	26.7	-7.76	19.67	20.9	1.23
	3	24.0	26.7	2.74	21.00	20.9	-0.10
23	1	31.0	27.4	-3.6	22.33	23.48	1.15
	2	32.0	27.4	-4.6	29.33	23.48	-5.85
	3	22.0	27.4	5.4	21.00	23.48	2.48
25	1	39.0	26.7	-12.26	32.00	23.33	-8.67
	2	27.0	26.7	-0.26	25.00	23.33	-1.67
	3	20.5	26.7	6.24	19.00	23.33	4.33
27	1	27.0	28.1	1.06	27.33	28.48	1.15
	2	30.5	28.1	-2.44	28.33	28.48	0.15
	3	30.0	28.1	-1.94	27.00	28.48	1.48

According to the results exposed in Table 4.1, the values of residuals mean the difference between the predicted value and the actual value.

The values achieved through Option 1 have a standard deviation around 6.1 mm likewise the values come from Option 2 presents a standard deviation around 4.7. Such difference exists because the data arrangement is different from each other. Therefore, is comprehensible that the Option 1 presents the range of residuals bigger than the ones presented by Option 2 for the trials exposed in Table 4.2.

Table 4.2 - Comparison between the results from Option 1 and Option 2.

Option	Limits	Values [mm]	Amplitude of the residuals [mm]
1	Maximum	+14.5240	26.0
	Minimum	-12.26	
2	Maximum	11.62	20.3
	Minimum	-8.67	

Comparing these values graphically is better to figure out the difference between the models.

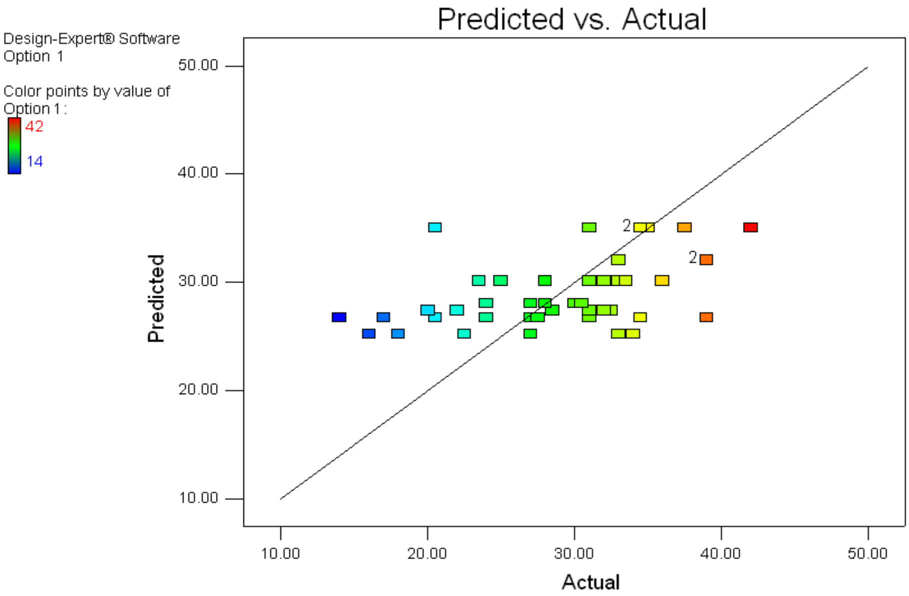


Figure 4.1 - Comparison between the actual and predicted values. Option 1.

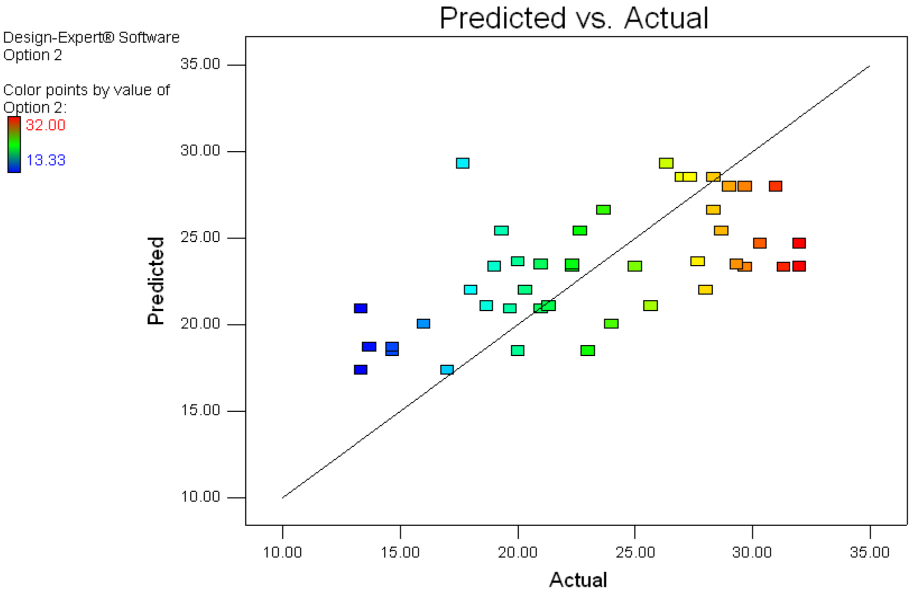


Figure 4.2 - Comparison between the actual and predicted values. Option 2.

The Figure 4.1 and Figure 4.2 show that, despite of the fact that the points are not totally settled down on the 45° straight line which means the ideal condition for the predicted value, they have certain accordance with the actual values. It is also obvious to realize that the way the points are laid down in Option 2 is better than the shape created in Option 1, in particular those points on the extremity of the curve (larger and smaller values found in the arrangement). In Option 2 they are spread along the line and on the other hand, the points in Option 1 are concentrated nearby the mean values.

Another way to verify the predicted value for both cases in study may be seen in the following Figures.

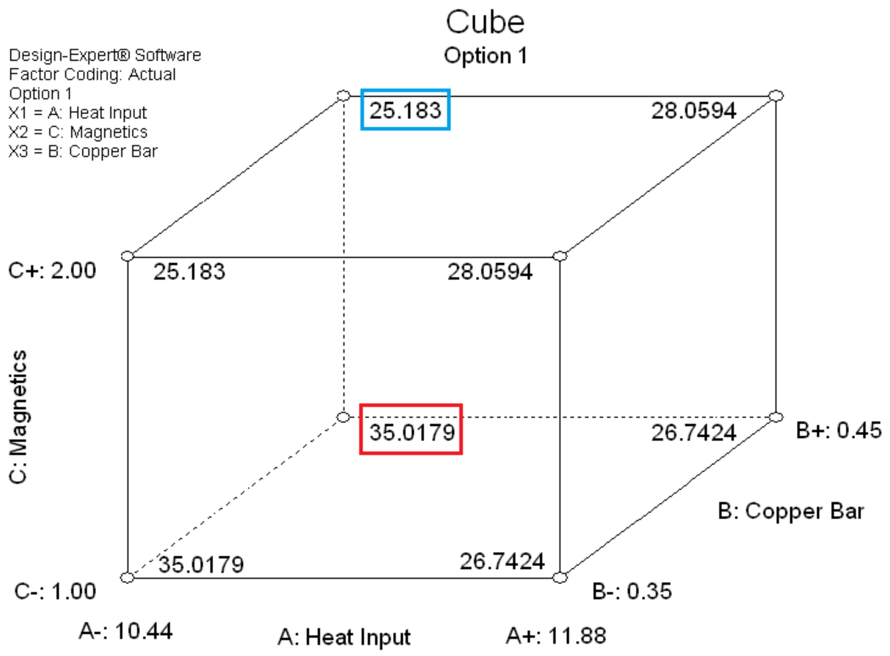


Figure 4.3 - Predicted values. Option 1.

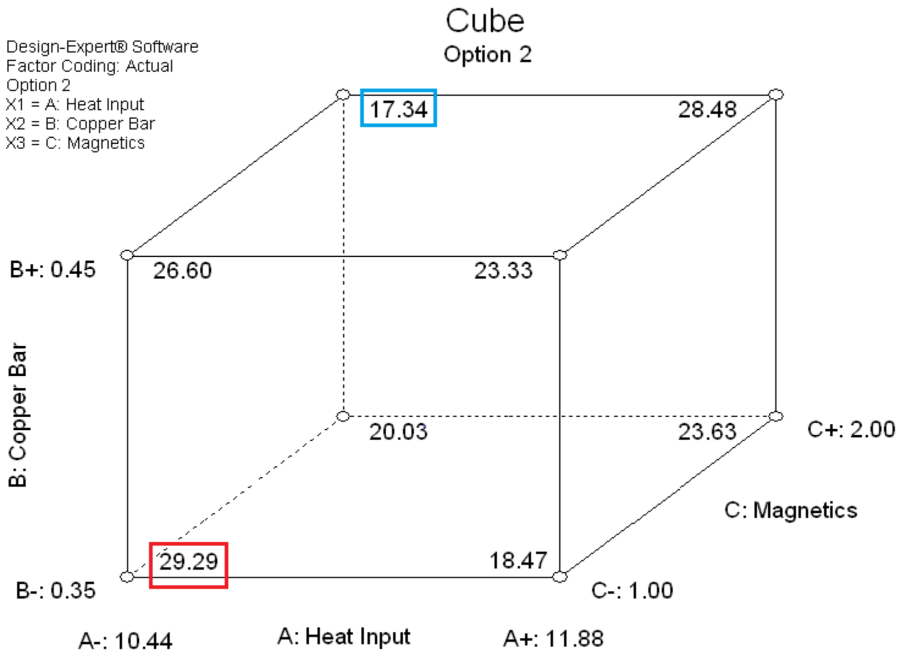


Figure 4.4 - Predicted values. Option 2.

On the Cube chart is possible to verify all the predicted values from the maximum and minimum level of the main factors. Highlighted in Figure 4.3 and Figure 4.4 are the maximum (red rectangle) and minimum (blue rectangle) results of deformation predicted for both models. The best condition to work i.e. the condition which presents the smallest value for deformation according to those models is:

Heat Input = 10.44 kJ/cm

Copper Bar pressure = 0.45 bar

Magnetics pressure = 2 bar

From now, assuming for the main factors larger and smaller values regarding those one used to build the model, is possible to realize the behavior of the welding deformation in Figure 4.5.

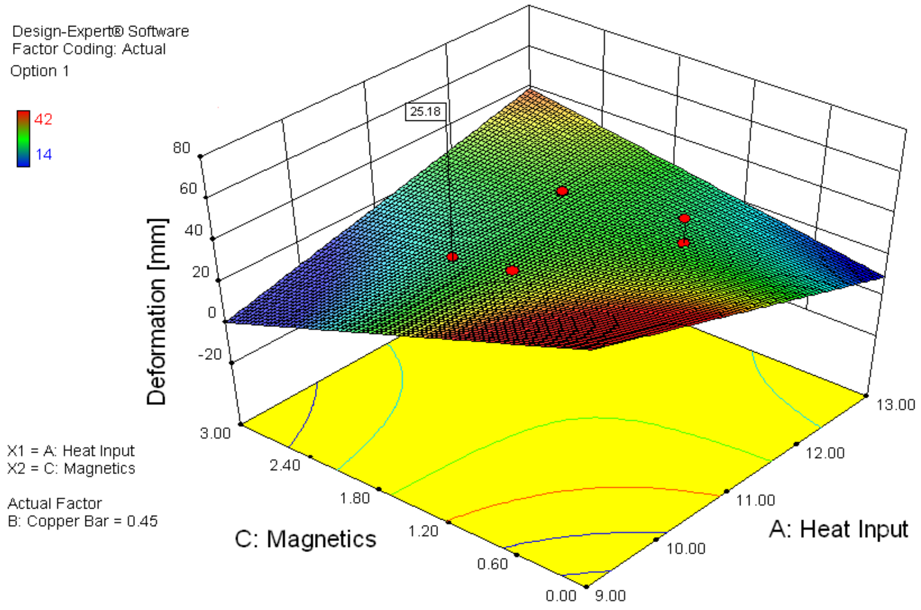


Figure 4.5 - Arbitrary predicted values. Option 1.

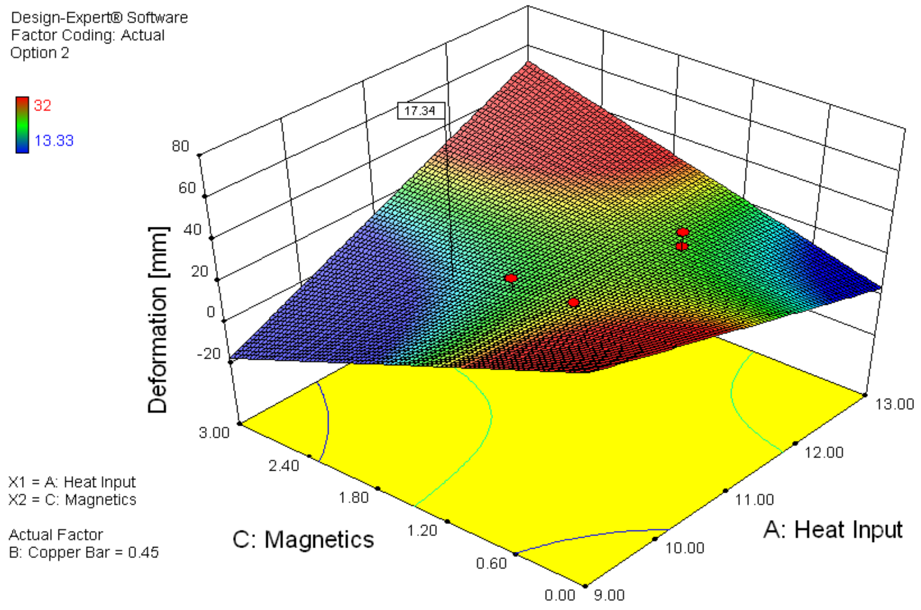


Figure 4.6 - Arbitrary predicted values. Option 2.

On this surface chart may be seen the comportment of the model when the values apart from the ones considered building the model are taken into account. Just to facilitate the understanding, the smallest values found in Figure 4.3 and Figure 4.4 were highlighted in both models. From there is possible to figure out that only 2 factor are spread in the chart and the Copper Bar value is fixed on the maximum condition. Therefore, assuming such combination, in Option 2 as much as the limit goes to the extremity (bigger or smaller values) the values for deformation trend to increase positively or negatively. The same address might be checked in Option 2 on the other hand with values of variation somewhat modest.

Continuing such evaluation, is convenient to verify the prediction around the trials 24 and 26, as mentioned in Data Processing section, such values would be used to check out the models and their equation as a partial evaluation, however a proper verification of accuracy with new trails using the models and the approach explained in this present work is strongly recommended in order to validate the models.

For the trails used in this work, the Table 3.13 shows their set of parameter and the Table 4.3 shows the values reached out through the Options 1 and 2 additionally the values of the residual for the trails 24 and 26.

Table 4.3 - Deformation values and residuals of trial 24 and 26.

Panel	Weld Seam	Option 1			Option 2		
		Actual Value [mm]	Predicted Values [mm]	Residual [mm]	Actual Value [mm]	Predicted Values [mm]	Residual [mm]
24	1	44.5	28.06	-16.44	33.33	26.06	-7.28
	2	23.5	28.06	4.56	16.00	26.06	10.06
	3	23.5	28.06	4.56	19.33	26.06	6.72
26	1	20.0	27.4	7.40	17.67	25.9	8.24
	2	51.0	27.4	-23.60	34.33	25.9	-8.43
	3	29.0	27.4	-1.60	30.00	25.9	-4.10

At the same way of thinking, the comparison between 2 models in terms of amplitude of residual variation:

Table 4.4 - Results from Option 1 and Option 2.

Option	Limits	Values [mm]	Amplitude of the residuals [mm]
1	Maximum	+7.40	31.0
	Minimum	-23.60	
2	Maximum	10.06	18.49
	Minimum	-8.43	

According to these results, the Option 2 demonstrates better results than Option 1, due to the smaller amplitude of residual variation.

After verifying the results of those 2 options with respect to statistical and dimensional point of view, it was understood that the model described by the Option 2 yielded better outcome than that one provided by the arrangement found in Option 1. Few reasons might justify these results, for instance the non consideration of the Copper bar effects in the model.

Moreover, another sight about the results is the fact that the models gotten from the DoE explain the average of the input values, i.e. the models work with the average deformation between the weld seam values. In case of compare the predicted value versus the average value of the weld seam, the standard deviation becomes smaller and it means that the model is able to explain the major of the results. These values are shown in Table 4.5.

Table 4.5 - Average values of the weld seam from Option 1 and Option 2.

Panel	Option 1				Option 2			
	Average Real Value (Weld Seam)	Predicted Value	Residual	Residual^2	Average Real Value (Weld Seam)	Predicted Value	Residual	Residual^2
1	37.00	32.03	-4.97	24.71	23.56	25.38	1.82	3.33
10	27.50	35.02	7.52	56.52	22.00	29.29	7.29	53.10
11	34.50	30.10	-4.40	19.36	31.17	24.66	-6.51	42.35
12	33.50	25.18	-8.32	69.17	20.00	20.03	0.03	0.00
13	38.00	35.02	-2.98	8.89	29.89	27.94	-1.95	3.79
14	29.83	30.10	0.27	0.07	27.78	23.31	-4.46	19.93
15	20.25	25.18	4.93	24.33	14.17	18.68	4.51	20.36
16	33.00	35.02	2.02	4.07	26.00	26.60	0.60	0.36
17	27.83	30.10	2.27	5.14	22.11	21.97	-0.14	0.02
18	21.50	25.18	3.68	13.56	15.17	17.34	2.17	4.72
19	25.17	26.74	1.58	2.48	19.22	18.47	-0.75	0.57
20	27.00	27.40	0.40	0.16	21.89	21.05	-0.84	0.71
21	26.00	28.06	2.06	4.24	23.84	23.63	-0.21	0.04
22	24.17	26.74	2.58	6.63	18.00	20.90	2.90	8.39
23	28.33	27.40	-0.93	0.87	24.22	23.48	-0.74	0.55
24	30.50	28.06	-2.44	5.96	22.89	26.06	3.17	10.04
25	28.83	26.74	-2.09	4.37	25.33	23.33	-2.01	4.03
26	33.33	27.40	-5.93	35.19	27.33	25.90	-1.43	2.04
27	29.17	28.06	-1.11	1.23	27.55	28.48	0.93	0.87
Standard Deviation				3.99				3.12

Therefore, for future evaluations regarding to this methodology is reasonable to evaluate the welding deformation on 5-mm-thick steel plate using the method explicated in Figure 3.34.

5 CONCLUSION

After the effort in the shipyard, numerous trials in the panel welding line, measurements and analyzing the results it is possible to draw a number of interesting conclusions from the investigation which can be formulated follows:

1. Unlike the main methodology proposed by several authors (FEM), the welding deformation in butt joints on 5-mm-thich steel plates is also possible to be predicted through a statistical method, as shown during this work.
2. Analysis governed by statistical principles may yield different results depending on how the data are input and this characteristic became an important issue encountered along that work. Because of this, some data arrangements were done and consequently verifications of the results intending to derive a numerical equation able to predict as accurate as possible the values of deformation similarly the ones collected during the measurement in the shipyard. Surprisingly, from each data arrangement it was possible to get a different equation and, sometimes, such equation did not take into account the influence of the all factor.
3. As shown in Figure 4.2, the model which considers the influence of all factors presents better results than the other model that did not take into account such influence. In this current work, for the analyzed models, considering the sum of the residual squared (given in Table 4.1), the accuracy differs around 57% from each other.
4. During the experiment and also from the shipyard staff experience it was stated that the factors considered during this work have significant influence on the welding-induced deformation hence, the influence of the factors considered in this work must be included in the model.
5. A numerical equation received from the statistical software, through the data arrangement attained by Option 2 presented reasonable results according to the data collected in the shipyard and therefore, it can be considered a satisfactory enough way to predict the welding-induced deformation in 5-mm-thick steel panel.

It is also remarkable to mention that all kinds of experiments, especially those performed under strict conditions related to the time and equipment availability, are subject to influences of the sources of error existents. Such sources should be identified and whenever possible avoided. For the future projects related to analyses through experiments the following recommendations can be given:

1. Measurement: always keep the same person, the same equipment and the same condition to measure.
2. Feedback: during the entire job there is a need to communicate intensively with the workers responsible for the process intending to raise them awareness about the experiment. If during the trials something goes wrong, these workers are in charge of the quality control, so they will adjust what is necessary to correct the problem. The experimenter must be aware about that.
3. Feedback: similarly, the key person must be identified before start of the experiment intending to give some help whenever it is necessary.
4. Noise in the model: verification of the initial condition (deformation) of the plates before start the welding process. It can help the experimenter to sort the noise out of the data processing, improving the overall results.

Few of these errors maybe made small influence in the final results presented, however the methodology used was carefully lead as far as possible.

As recommendation for continuity of this work, a number of extra trials should be performed and the data analyzed based on the methodology adopted in section 3.4.1 intending to verify the real accuracy of the model. Although it has not been presented, other different data arrangements to define the values of the welding deformation were developed aiming to get better results, such as: average values amongst all of the point or considering the small value as a reference, or even trying to organize the measures around the weld seam as a matrix and understanding them like that, the values of deformation could be considered as Eigen values of these matrix. Hence, another suggestion for future works can be drawn as the development of different data arrangement as a result different numerical equation to predict the welding deformation

6 ACKNOWLEDGEMENT

This thesis was developed in the frame of the European Master Course in "Integrated Advanced Ship Design" named "EMSHIP" for "European Education in Advanced Ship Design", Ref.: 159652-1-2009-1-BE-ERA MUNDUS-EMMC.

I would like to thank the Polish shipyard for the time spent there to develop the experiment presented in this work, especially to department of metrology, to Mr. Piotr Kurzyna for the friendly help and technical assistance and translations and to Professor Boshidar Metschkow for the opportunity to work and also for all wisdom and experience shared.

I also thank Professor Tadeusz Graczyk for the guidance and useful suggestion for this work as well as I acknowledge and thank for the effort made by Professor Maciej Taczała reviewing this thesis and help me with the language issues, even though he guided other classmates.

In an overall view, I would like to thank all the people that helped me during the course, such as Professor Guajarino Araújo for the hints during the internship, my classmates for the friendship, Audrey Méllote for her friendly and useful assistance, Professor Charlemagne Danoh and Professor Philippe Rigo for the opportunity to study and expand my horizon.

Thank God for all strength to be here. To my family, I am grateful for all of the incentive, trust and love spent even being far away from them, my mother Lucelina Sena, and my father Cezar Batista and my relatives.

Finally and most importantly, a special thank to my lovely wife Juliana Sena for all patience, dedication, comprehension, help and valuable company during this tough time. I dedicate this thesis to her.

7 REFERENCE

Awang, M., 2002. The effects of process parameters on steel welding response in curved plates. Thesis of Master of Science in Mechanical Engineering. West Virginia University.

Birk-Sørensen, M., 1999. Simulation of welding distortions in ship section. Industrial PhD Thesis. Technical University of Denmark.

Brust, F.W. and Scott, P., 2007. Weld Distortion Control Methods and Applications of Weld Modeling. *Transactions,* SMiRT 19, Toronto, Paper# B05/1.

Deng, D., Murakawa, H. and Ueda, Y., 2002. Theoretical Prediction of Welding Distortion Considering Positioning and the Gap between Parts. *The Proceedings of the Twelfth International offshore and polar engineering conference.* Available from: http://www.isope.org/publications/proceedings/ISOPE/ISOPE%202002/Volume4/4054p337.pdf [accessed 17 November 2011].

Buffa, G., Ducato, A. and Fratini, L., 2011. Numerical procedure for residual stresses prediction in friction stir welding. *Finite Elements in Analysis and Design*, 47, 470–476.

Fortes, C., 2005. Soldagem MIG/MAG [online]. ESAB. Available from: http://www.esab.com.br/br/por/Instrucao/biblioteca/upload/1901104rev0_ApostilaSoldagemMIGMAG.pdf [accessed 19 November 2011].

Fortes, C., 2004. Arco Submerso [online]. ESAB. Available from: http://www.esab.com.br/br/por/Instrucao/biblioteca/upload/1901100rev0_ApostilaArcoSubmerso.pdf [accessed 07 November 2011].

Franceschini, G. and Macchietto, S., 2005. A numerical experiment design study on a biodiesel production process. *Computer Aided Chemical Engineering*, 20, 349-354.

Funderburk, R.S., 1999. Key Concepts in Welding Engineering. *Welding Innovation*, 16, N° 1.

Galvanin, F., Barolo, M. and Bezzo, F., 2010. A framework for model-based design of experiments in the presence of continuous measurement systems. *Dynamics and Control of Process Systems*, 9, Part# 1.

Galvanin, F., Barolo, M. and Bezzo, F., 2008. Towards on-line model-based design of experiments. *Computer Aided Chemical Engineering*, 25, 349-354.

Iranmanesh, M. and Babakoohi, S., 2008. The analysis of longitudinal shrinkage in butt welding. International Journal of Engineering, Transactions B: Applications, 21 (2), 197-202.

Johnson, R. and Bhattacharyya, G., 1987. *Statistics, principles and methods*. USA: John Wiley & Sons, Inc.

Kaufmann, H., 2003. Efficient production of stiffeners for shipbuilding. *The ESAB welding and cutting journal*, 58 (1), 9-15.

Kou, S. 2003. *Welding metallurgy*. 2nd ed. USA: John Wiley & Sons, Inc.

Lukkari, J. and Vähäkainu, O., 2003. How much heat can various steels and filler metals withstand? *The ESAB welding and cutting journal*, 58 (1), 18-23.

Murakawa, H., Deng, D., Rashed S., and Sato, T., 2009. Prediction of Distortion Produced on Welded Structures during Assembly Using Inherent Deformation and Interface Element. *Transaction of JWRI,* 38 (2).

Sofuoglu, H., 2006. A technical note on the role of process parameters in predicting flow behavior of plasticine using design of experiment. *Journal of Materials Processing Technology*, 178 (1-3), 148-153.

Sukovoy, O. and Kuo, C., 2003. A risk-based method for minimizing welding distortion in steel ship production. *Engineering for the Maritime Environment*, 217 (3), 123-131.

Tajima Y., Rashed S., Okumoto, Y., Katayama, Y. and Murakawa, H., 2007. Prediction of Welding Distortion and Panel Buckling of Car Carrier Decks using Database Generated by FEA. *Transaction of JWRI*, 36 (1).

Törnblom, S., 2007. *Undermatching Butt Welds in High Strength Steel*. Master Thesis. Luleå University of Technology.

Tsai, C. L., Park, S. C. and Cheng, W. T., 1999. Welding *Distortion of a Thin-Plate Panel Structure* [online]. American Welding Society. Available from: http://www.aws.org/wj/supplement/may99/TSAI.pdf [accessed 12 December 2011].

Vanli, O. A. and Michaleris, P., 2001. Distortion Analysis of Welded Stiffeners. *Journal of Ship Production*, 17 (4), 226-240.

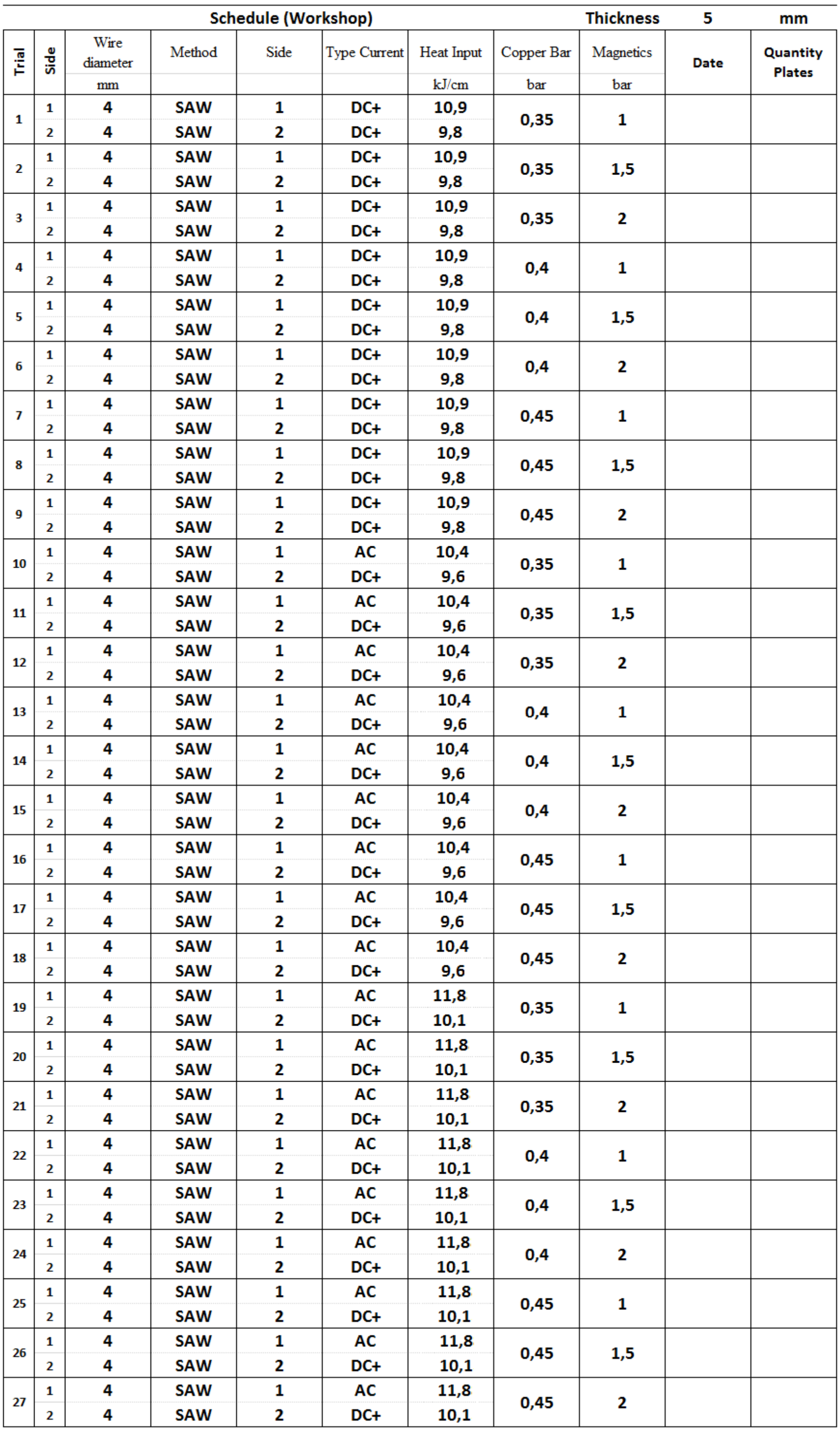
Wang, R., Zhang, J., Serizawa, H. and Murakawa, H., 2009. Study of welding inherent deformations in thin plates based on finite element analysis using interactive substructure method. *Materials and Design*, 30 (9), 3474 – 3481.

WTIA, 2006. *Distortion control in shipbuilding* [online]. Welding technology institute of Australia. Available from: http://www.wtia.com.au/pdf/TGN-D-04%20Distortion%20control%20in%20shipbuilding.pdf [Accessed: 20 November 2011]

Yajiang, L., Juan, W., Maoai C. and Xiaoqin, S., 2004. Finite element analysis of residual stress in the welded zone of a high strength steel. *Bulletin of Materials Science*. 27 (2), 127 – 132.

8 APPENDICES

8.1 Experiment scheme available at workshop



Schedule (Workshop) **Thickness** **5** **mm**

Trial	Side	Wire diameter	Method	Side	Type Current	Heat Input	Copper Bar	Magnetics	Date	Quantity Plates
		mm				kJ/cm	bar	bar		
1	1	4	SAW	1	DC+	10,9	0,35	1		
	2	4	SAW	2	DC+	9,8				
2	1	4	SAW	1	DC+	10,9	0,35	1,5		
	2	4	SAW	2	DC+	9,8				
3	1	4	SAW	1	DC+	10,9	0,35	2		
	2	4	SAW	2	DC+	9,8				
4	1	4	SAW	1	DC+	10,9	0,4	1		
	2	4	SAW	2	DC+	9,8				
5	1	4	SAW	1	DC+	10,9	0,4	1,5		
	2	4	SAW	2	DC+	9,8				
6	1	4	SAW	1	DC+	10,9	0,4	2		
	2	4	SAW	2	DC+	9,8				
7	1	4	SAW	1	DC+	10,9	0,45	1		
	2	4	SAW	2	DC+	9,8				
8	1	4	SAW	1	DC+	10,9	0,45	1,5		
	2	4	SAW	2	DC+	9,8				
9	1	4	SAW	1	DC+	10,9	0,45	2		
	2	4	SAW	2	DC+	9,8				
10	1	4	SAW	1	AC	10,4	0,35	1		
	2	4	SAW	2	DC+	9,6				
11	1	4	SAW	1	AC	10,4	0,35	1,5		
	2	4	SAW	2	DC+	9,6				
12	1	4	SAW	1	AC	10,4	0,35	2		
	2	4	SAW	2	DC+	9,6				
13	1	4	SAW	1	AC	10,4	0,4	1		
	2	4	SAW	2	DC+	9,6				
14	1	4	SAW	1	AC	10,4	0,4	1,5		
	2	4	SAW	2	DC+	9,6				
15	1	4	SAW	1	AC	10,4	0,4	2		
	2	4	SAW	2	DC+	9,6				
16	1	4	SAW	1	AC	10,4	0,45	1		
	2	4	SAW	2	DC+	9,6				
17	1	4	SAW	1	AC	10,4	0,45	1,5		
	2	4	SAW	2	DC+	9,6				
18	1	4	SAW	1	AC	10,4	0,45	2		
	2	4	SAW	2	DC+	9,6				
19	1	4	SAW	1	AC	11,8	0,35	1		
	2	4	SAW	2	DC+	10,1				
20	1	4	SAW	1	AC	11,8	0,35	1,5		
	2	4	SAW	2	DC+	10,1				
21	1	4	SAW	1	AC	11,8	0,35	2		
	2	4	SAW	2	DC+	10,1				
22	1	4	SAW	1	AC	11,8	0,4	1		
	2	4	SAW	2	DC+	10,1				
23	1	4	SAW	1	AC	11,8	0,4	1,5		
	2	4	SAW	2	DC+	10,1				
24	1	4	SAW	1	AC	11,8	0,4	2		
	2	4	SAW	2	DC+	10,1				
25	1	4	SAW	1	AC	11,8	0,45	1		
	2	4	SAW	2	DC+	10,1				
26	1	4	SAW	1	AC	11,8	0,45	1,5		
	2	4	SAW	2	DC+	10,1				
27	1	4	SAW	1	AC	11,8	0,45	2		
	2	4	SAW	2	DC+	10,1				

Appendix A1 - Scheme defining the DoE.