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# OPTIMIZING THE SHIP CONSTRUCTIONS BY AUTOMATIC LINE HEATING FORMING PROCESS BASED IN NUMERICAL SIMULATION AND ARTIFICIAL INTELLIGENCE

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**Abstract.** This paper presents the development of a novel automatic lineheating forming machine based on intensive application of the numerical simulation and artificial intelligence. The forming of certain parts of the shell of the ships can be done by heating forming or mechanical forming. Line heating forming is usually a more flexible process, and therefore, it is more useful. The principal problem with line heating forming is that it is very time consuming, manual and needs very qualified workers. In this research, line heating forming is studied looking for the best way to automate the process.

Numerical models were developed based on finite element methods to simulate the process of heating, cooling and finally forming of the plates. The models were tested and validated against experimental test over small plates. However, as numerical models have extremely long computational times demanding high computational capacities; they are not directly applicable in a real time scenario, as it is needed.

Finally, after the mathematization of this knowledge and making use of it, it was developed a software based on artificial intelligence. Using an informed heuristic search strategy, this software predicts the optimal set of heating lines, their sequence and velocity to be applied over the plate to obtain the final shape. The developed system was tested to show its feasibility. As a consequence, there is a significative reduction in computational time allowing the system to be applied in a soft real-time environment. This model will help shipyard manufacturers determine the positions and trajectory of torch for the flame heating lines and their heating parameters to form a desired shape of plate.

## 1 INTRODUCTION

The geometry of the hull of a ship is designed to equip navigability, maximizing capacity and minimizing fuel consumption. This design results, in many cases, in complicated three-dimensional geometries, which are manufactured by cutting and forming flat steel plates which are then assembled. The need to get these forms in sheets of different thicknesses and qualities has led to develop different methods of bending with an approximation to the required forms achieved.

Mechanical cold forming raises the issue of limited geometries imposed by the rollers, the constraints imposed by the bending machines and the high costs of presses, especially when ships are not serialized products, and hull plates are often unique pieces that are rarely repeated from one design to another.

Alternatively, line heating forming allows flexibility in geometry unattainable by mechanical means. Currently, this process is accomplished by applying lines manually with a torch, followed by intense cooling, with some linear patterns on the sheet, which becomes in a forced thermal distortion curvature (Fig.1).

The flame line heating forming is a non-contact method of producing bending, spatial forming and alignment of metallic and nonmetallic components through the controlled application of heat input over the plates which introducing thermal stresses into a work-piece.

**Figure 1**: Manual line Heating forming

However, location, sequence and mode of application of these patterns or lines is based entirely on the experience of a few gifted operatives skill necessary for this operation, which is also unhealthy for the high levels of noise, fumes and other risks associated with the process.

Double curved plates are especially critical to the quality parameters of the vessel (speed, consumption, etc.) as they affect hydrodynamics [1], and its shape, therefore, should be accurate.

While there have been notable attempts to systematize the knowledge or automate the process of line heating forming [2], the fact is that uncertainty comes from the lack of stability in the results of the application of heat by the thermal sources used (torches) and the strong dependence of skilled and experienced workforce.

From the 90th some researchers as Vollertsen et al. [3–5] have proposed that three mechanisms of line heating forming process: the temperature gradient mechanism (TGM), buckling mechanism (BM) and upsetting mechanism (UM), can be used to produce heating forming. Intensives studies have been done on modeling the line heating forming process as: several analytical models, the finite difference method or finite element models.

The finite element methods have shown they can accurately capture the plate stiffness and curvature. However, they require high computational time and therefore it is not feasible predict complex shapes and sequences using finite element method [6]. A systematic methodology for determining the heating pattern to form a desired shape using thermal energy from gas combustion has not been developed yet.

For that reason, in this work we propose an artificial intelligence system that makes use of the knowledge generated by finite element methods. Moreover, it assumes some valid simplifications of the problem that, through a heuristic search strategy, allows to predict the optimal set of heating lines, their sequence and velocity to be applied over the plate to obtain a desired final shape. As a consequence, there is a significative reduction in computational time allowing the system to be applied in a soft real-time environment.

## 2 FINITE ELEMENT METHODOLOGY

The distortion/forming takes place in a metal whenever the plate suffers a thermal load. It generates stresses greater than the yield stress point, so the deformation moves from the elastic to the plastic range. The thermal load causes a gradient of temperature and thermal expansion resulting in the bending of the plate in a convex shape to the heated surface [7]. Therefore, determination of temperature field is the prerequisite for predicting the deformation of the plate.

The heatforming simulation problem has a complex nature; the process is highly nonlinear and couples thermal, mechanical and metallurgical fields: thermal loads generate changes in the mechanical fields, high temperatures and high cooling rates can lead to phase change and metallurgical transformations what makes the material properties dependent on the temperature and metallurgical phase proportion. The cycle time is very long because the cooling is usually slow and the loads and boundary conditions can change with the time and temperature. FEM requires transient thermal and quasi-static mechanical analysis, which may involve thousands of time increments.

Nowadays, it is not possible to simulate the whole physics involved in the forming process in a realistic way, as detailed Lindgren [8]. Some simplifying alternatives were studied by Ueda [9]. At present the FEM simulation of weld usually use Lagrange mesh. In this work, the heat source was modeled 3D conical approximation Eq. 1 with a Gaussian distribution.

$$P = \int Q(x, y, z, t) = Q_0 \cdot e(-\frac{r^2}{r_0^2}) \tag{1}$$

where $Q$ is the power of the source, $Q_f$ and $Q_r$ are the energy in the front and rear of the source, $a$, $b$ and $c$ are the dimensions of the elliptical shape of the source, $r$ are the radius of the Gaussian source over the plate, $v$ is the speed of the source and $x$, $y$ and $z$ are the position of the source over the plate.

The heat line forming was defined as thermo-mechanical coupling. However, in this forming process one can use a simplification by decoupling of the process with an initial thermal simulation and then posterior mechanical analysis. This is possible because the mechanical effect does not disturb the thermal fields as shown in Lindgren [10]. The same mesh is used for both thermal and mechanical calculations.

These simulations require large computational efforts to obtain reliable solutions because a dense mesh is necessary to capture the high thermal gradients caused by the heat source. Also a lot of iterations are necessary due to the nonlinearity of the plastic behavior of the system.

Moreover, the final time process can be long and the step time should be short. The thermo-metallurgical-elastoplastic model approximation has showed a great accuracy of line forming [11], but in the case of big assemblies the cost of computation increases significantly.

$$\dot{\varepsilon} = \dot{\varepsilon}^{e} + \dot{\varepsilon}^{p} + \dot{\varepsilon}^{tp} + \dot{\varepsilon}^{th} \qquad (2)$$

The presented study is performed having into account the strains in Eq. 2, so strains due to elastic and plastic domain ($\dot{\varepsilon}^{e}$, $\dot{\varepsilon}^{p}$), the thermal strains ($\dot{\varepsilon}^{tp}$) and the strains produced by the phase transformations ($\dot{\varepsilon}^{th}$). The plasticity is calculated with a linear kinematic hardening approximation for the elastic-plastic constitutive model [11], this simplification is possible due to the Naval A steel used is a mild steel and the kinematic approximation is accurate enough in a single pass line heating. Also, it was used a metallurgical model based on Johnson-Mehl- Avrami [12] and Koistinen and Marburger [13] models.

Sysweld code was the tool used to develop the heatline model. The finite element equation for transient heat transfer analysis can be expressed as follows: $[C][\dot{T}]+[K][T]=[Q(t)]$ where $[C]$ is the specific heat matrix, $[\dot{T}]$_ the time derivative of temperature, $[K]$ the heat conductivity matrix, $[T]$ the temperature and $[Q(t)]$ the heat flux column. The non linear transient dynamic structural equation based on FEM can be written in the matrix form as follows: $S(T)[u(t)]=[F^{th}(t)]$, where thermal load is $[F^{th}(t)]$, $S(T)$ the temperature dependent stiffness matrix and $[u(t)]$ the nodal displacement vector.

## 3 FINITE ELEMENT VALIDATION

Along the project it was studied several strategies of line heating forming done by experts in shipyards, also laboratory experiments were done too. In laboratory it was used small plates under one heatline alone. The idea behind this work was finding individual behavior of the line heating forming. Also, simple cases of the DoE were used to validate the numerical model. Line heating experiments were conducted to verify the thermal model and the mechanical model. All the experiments were performed at AIMEN Technology Centre.

To carry out the propane gas heating process characterization, heatline was applied over small plates (600x600mm) and one thickness (12mm) under different density power configurations. The plate is a cantilever kind of structure, totally free at one end and with strong clamping at the second one. The propane heat line pass was carried in the middle of the plate.

The workpiece material is considered isotropic. Each materials properties such as modulus of Young, yield stress, or the heat transfer properties as thermal conductivity and specific heat are temperature dependent. No melting is involved and no external forces are applied in the forming process.

For this experiment a propane torch was used for heating a horizontal plate. The torch of propane used as heating source is very complex phenomenon due to combustion between propane gas and oxygen. For this reason, a simplified method based in a conical Gaussian source was used. In this method, the energy from torch was introduced in a volume of control inside the material.

A FE method was used to simulate the lineheating forming process. Some experimental outcomes were compared against the results obtained through the numerical simulation. The performed cases differing only in the heatsource parameters are presented in Table 1.

**Table 1**: Cases of study

| Id | Gas | Dimensions | Thickness | Speed torch | Gas presure | O2 presure | Gas flow (l/min) | O2 flow (l/min) | Spot distance |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Propane | 600x600 | 12 | 6.7mm/s | 1 | 3,5 | 800 | 4500 | 21mm |
| 2 | Propane | 600x600 | 12 | 6.7mm/s | 1 | 3,5 | 1000 | 4500 | 21mm |
| 3 | Propane | 600x600 | 12 | 6.7mm/s | 1 | 3,5 | 1000 | 2800 | 21mm |
| 4 | Propane | 600x600 | 12 | 10mm/s | 1 | 3,5 | 1000 | 2800 | 21mm |
| 1 | Acetylene | 600x600 | 12 | 6.7mm/s | 0,5 | 3,5 | 500 | 750 | 20mm |
| 2 | Acetylene | 600x600 | 12 | 5mm/s | 0,5 | 3,5 | 500 | 650 | 8mm |
| 3 | Acetylene | 600x600 | 12 | 5mm/s | 0,5 | 3,5 | 500 | 650 | 3mm |
| 4 | Acetylene | 600x600 | 12 | 3,3mm/s | 0,8 | 3 | 500 | 650 | 18mm |

The only load for each case was the combustion source, but the models need some boundary conditions for the existence of unique solution. The boundary conditions necessary to assure the existence of a unique solutions are defined as any type of kinematic restriction and the heat environment temperature exchange. Also, an initial temperature for all nodes it was necessary to be set up to complete the initial-boundary problem. The simulation was carried at complete cooling when the complete springback phenomenon had taken place.

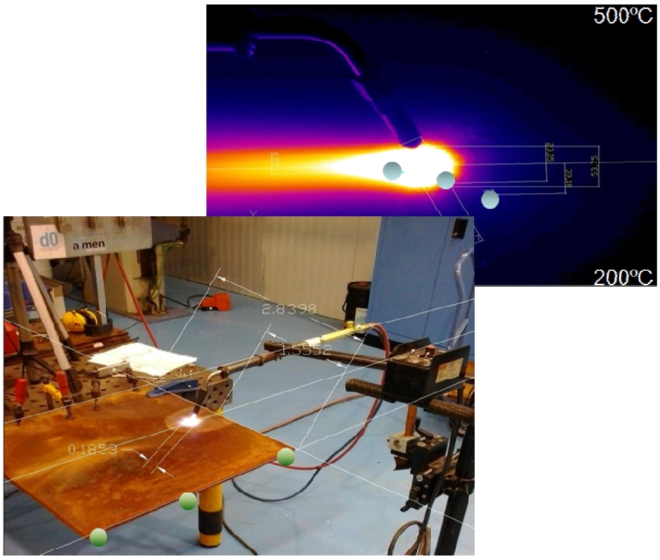

**Figure 2**: Conditions, restrictions for heatline modeling and thermographic.

It was used motorized arm to guarantee uniform and continuum movement, distance and speed of line heating.

The Fig. 2 presents the trajectory of heatsource following a straight line in the width of plate; the clamping condition where assured by the 3-axis displacements restrained through of Dirichlet conditions on nodes. After the process (including the cooling stage) the plate was unclamped.

With the plate complete cold and unclamped, the distortion was measured at the free opposite end of the plate in real time process, where its value reaches the maximum.

The evolution of temperature field over the plates was recorded with a thermocam for the back side. Three points (P1, P2 and P3) over the plate were chosen to be compared in the meaning of simulation and experimental results (Fig. 2). In those points of control, the heating and cooling stage was registered. After the computation of the model it can see the field of temperatures and the final deformation state (forming plate), Fig. 3.

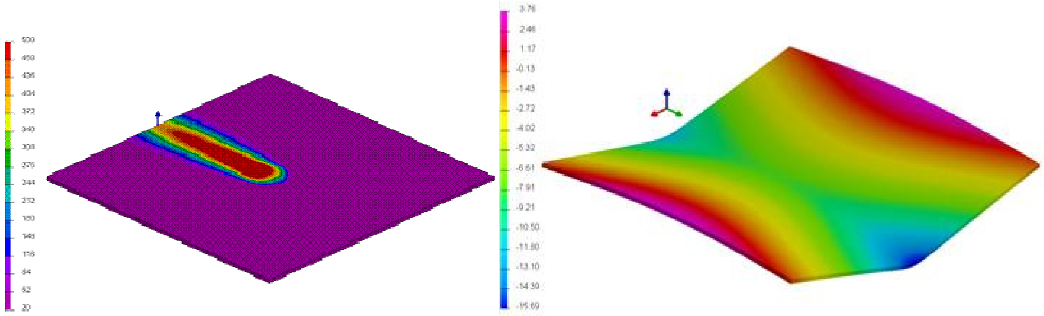

**Figure 3**: Results of the thermomecanical FEM model

The comparative results obtained by both methodologies were shown in the next figures (Fig. 4 and 5). The graphics from Fig. 5 show the temperature evolution along the three points (Fig. 2.). Virtual sensors over the FEM plate were deposited in the same geometric positions. The evolution of the temperature on thermocouples and nodes was done (Fig. 4.). The thick lines show the results from experimental measurements and the thin line of the FEM model. The three cases show an excellent behavior. Therefore the thermal model is validated.

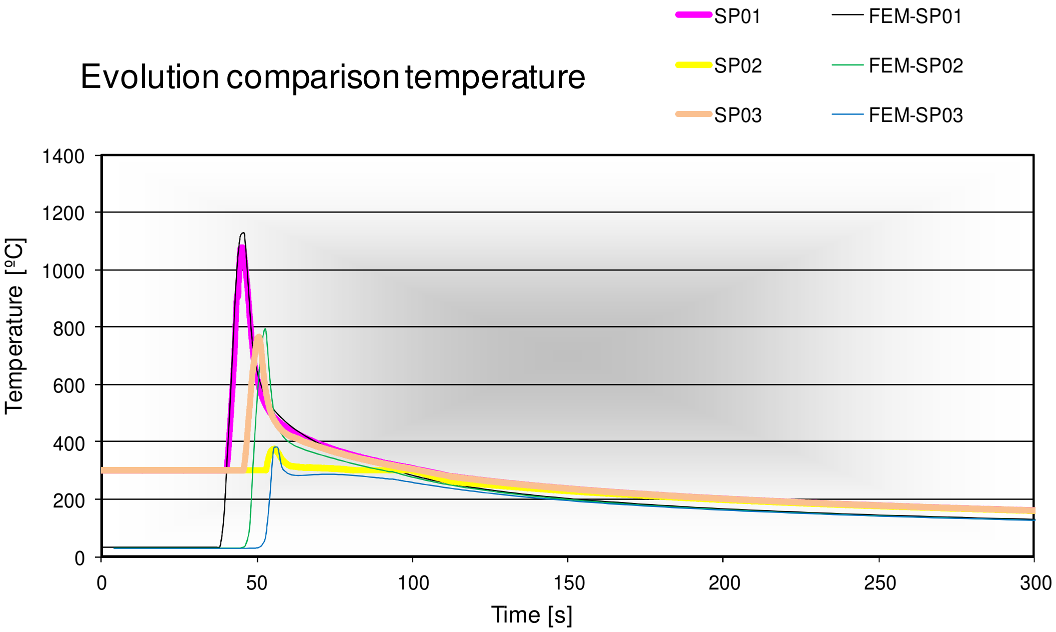

**Figure 4**: Temperature evolution comparison FEM vs Experimentación

After the thermal validation of a reference case, it was done the mechanical validation. The maximum flexion was analyzed and compared between simulation and experimentation, for each case (Fig. 6.). Every case shows excellent agreement between both methodologies.

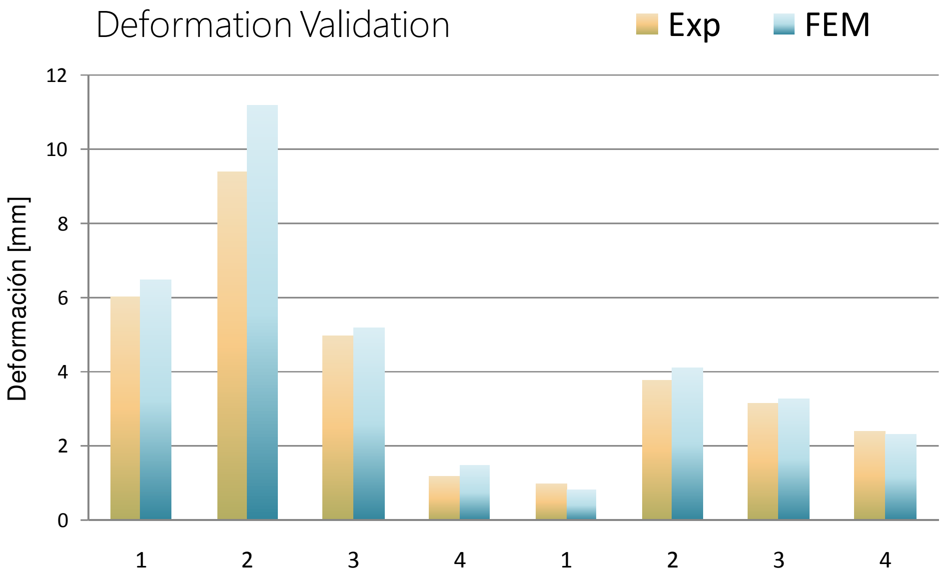

**Figure 5**: Distortion comparison between experimental vs. results of simulation

The differences obtained in every case are lower than 15%, thus the model is representative. It is demonstrated that the methodology applied in the numerical simulation is able to predict the distortion phenomenon with great accuracy in every cases. With these cases the validation is the numerical model, the material characterization and the operative conditions.

## 4 AUTOMATIC FORMING DEVELOPMENT

As seen in the preceding section, the FEM results play a useful role in helping test hypotheses ascertaining experimental results and helping explain observed phenomena. During the project a huge quantity of FEM cases were done. It was parameterized the geometry of the plate (including the thickness), the speed, orientation, position and length of the torch movement, the heatpower of the heatsources and the strategy of the heat passes to obtain the different deformations (shrinkages or transversal and longitudinal distortion) and different shapes in general.

With the exhaustive simulations a database of behavior of line heating forming was done. This database together with experimental test was worth to develop a new intelligent system able to determine the optimal pattern of heat lines (their location, sequence and speed of application) needed to form steel plates in order to obtain a desired 3D-geometry.

The problem of generating a sequence of actions to reach a given goal can be seen as a planning problem, which in Artificial Intelligence can be solved by using an informed heuristic search strategy [14]. This type of strategies considers that, at any time, the problem is in a state that can be changed by the occurrence of an action. Therefore, to solve the planning problem a state graph is used in which each node represents a state of the problem and each arc is an action that allow to transit from one state to another. As shown in Fig. 6, the graph employed in the lineheating forming system is characterized by:

- An initial state, which in our case is the representation of the real current shape of the plate we want to form. The shape could be flat, at the beginning of the forming process, or it could be any other convex shape when an already formed plate is being refined.
- Several intermediate states, each of them representing semi-formed plates as result of applying a given set of heat lines to the initial state.
- A final state, which is plate that accomplishes the desired shape specification. There are many valid final plates as a minimum difference (tolerance) is allowed between the desired shape and the real final shape.
- The arcs represent a transition function, i.e. the operators that allow to transit from one state to another. In our case, there is only one operator that consists of simulating the application of only one heat line to the plate, in a given position and with a specific speed of the heat source.

It is important to remark that both the intermediate and the final states are the estimated result of applying a given set of heat lines to the initial state done by simulating the distortion/forming that takes place in a metal whenever the plate suffers a thermal load.

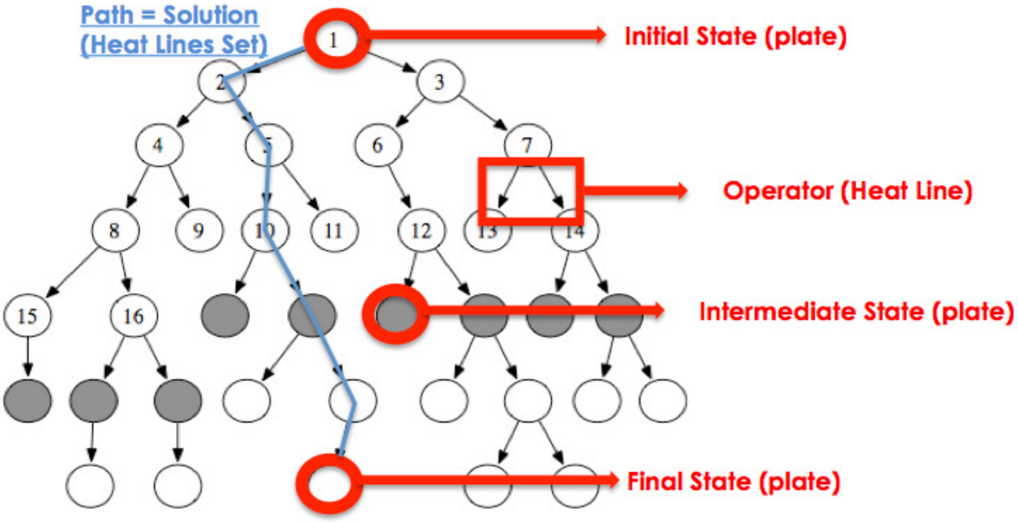

**Figure 6**: State graph used by the heuristic search system.

The heuristic search tries to find the path to obtain from the initial state a final state, i.e., a solution for our problem. Specifically, we employed the A* search algorithm [14]. This algorithm guarantees to find the lowest cost path between an initial and an objective state, if certain conditions are met. This approach coincides with the forming problem, as the goal is to find the set of heat lines that allows obtaining the desired plate in the minimum amount of time.

To reduce the search possibilities through the graph branches, A* only explore the most favorable states, i.e. those that are more plausibly to be part of the solution. With this aim, at each step of the search, each intermediate state is assessed by using an evaluation function as a sum of two factors:

- The cost to reach the intermediate state from the initial state. In our case, this cost is the time it takes to apply the heat lines indicated in the path that goes between the two states, taking into account the length of the heat lines and the speed of the torch.
- The heuristic, which is an estimation of the cost of a hypothetical path from the intermediate node to the goal node, i.e. it is an estimation of the time it would take to form the plate that is in an intermediate state to reach the desired plate. It is a requirement for the A* to be able to obtain the optimal solution that this heuristic function must never overestimate the cost and it is usually formulated by proposing a function that calculates the exact cost in a simplified version of the problem being treated [15]. In this case, the distortion angle between the objective and the current form is calculated and, based on that, the minimum number of heat lines at the fastest speed is used to calculate de heuristic cost.

At each step, the algorithm selects the lowest cost state and generates all the possible next states that can be reached with the application of another heat line. Afterwards, these new states are tested to check if any of them correspond with a valid final plate, i.e., one that it is similar enough to the desired plate within a margin of error.

For the development of this search algorithm it was indispensable to acquire knowledge about the forming process and the behaviour of metal plates when the heat is applied. This knowledge was acquired from industrial manuals, technical reports and, overall, form the experiments and simulations of heating, cooling and finally forming of the plates done with the numerical models, as described in the previous sections. This knowledge is mainly included:

- In the Search Operator that determines which heat line can be applied from a given state, whether as a restriction (e.g. minimum distance between lines) or as a behaviour law of the line heating forming (e.g. longitudinal and transversal distortion angles for a given temperature, thickness and dimensions of the plates, orientation and length of the heat lines…)
- In a prediction system that estimates the intermediate states, i.e., simulates the deformations and obtains the new shape of the plate after applying each heat line.

Finally, thanks to this knowledge and the assumed valid simplifications of the problem, the intelligent system returns the set of heat lines that allows obtaining a valid final plate in the minimum possible forming time with a significative reduction in computational time thus allowing the system to be applied in a soft real-time environment.

## 5 INDUSTRIAL VALIDATION

In order to show the efficiency and accuracy of the simplified model, it was performed a complete forming over a big dimension plate (1500x1500mm). The plate is flat initially and the final shape should be a typical U-Shape. The most efficiency strategy to obtain that shape is performing linear longitudinal parallel heat lines. The final shape (Fig. 7.) of the part of hull was introduced on the automatic forming system. The intelligent system predicts seven heat line passes (Fig. 7).

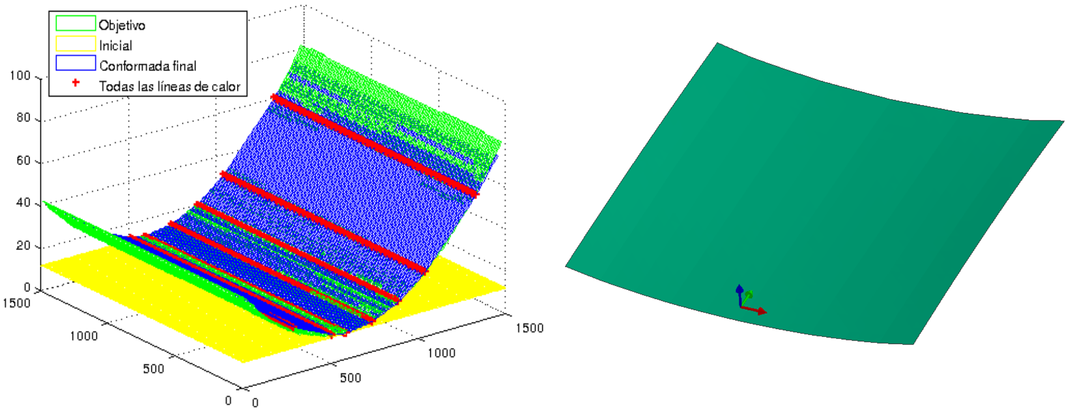

**Figure 7**: CAD of shape objective (right) and sequence predicted (left)

The sequence obtained from the IA system developed on ConforShip project was tested on FEM model. The transversal shape of the plate was compared, Fig. 8. Nonlinear thermal analysis is carried on first, followed by mechanical analysis. The results were very similar; therefore the simplified model works properly.

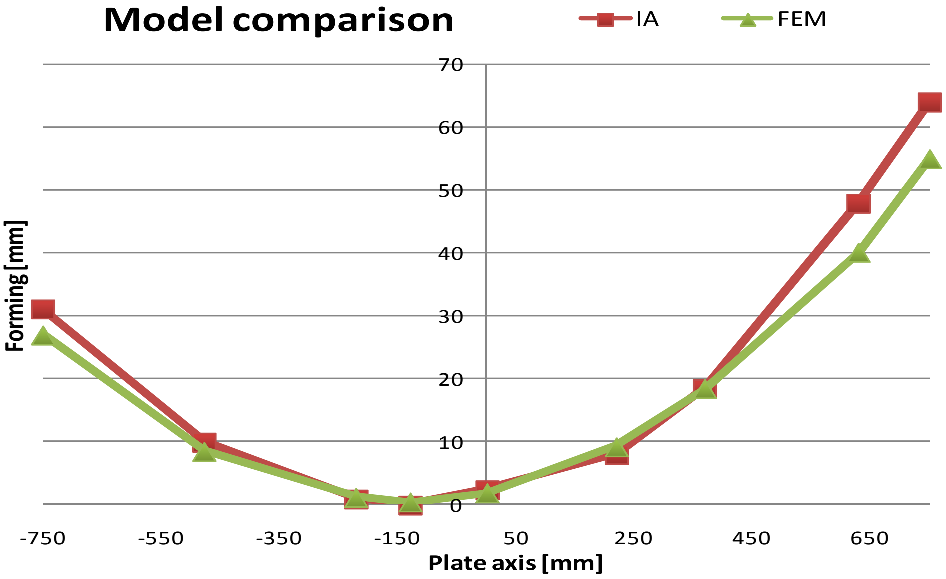

**Figure 8**: Comparison forming between FEM vs AI

All FEM computations were executed on a workstation i7-4470 running at 3400 MHz and 32Gb. The FEM calculation was performed in two macrosteps (three passes and four passes). This decision was taken based on the results from the heuristic software. The FEM simulation needs 188 hours to perform the computation. The system developed in ConforShip requires 47 seconds to perform the prediction of the forming and the sequence.

## 6 CONCLUSIONS

- The line heating forming has the advantage of process flexibility. Also, this process is usually more economic than other processes, mechanical (pressure, rolling…) or thermal forming (Laser or induction).
- A thermo mechanical model was developed to compute the deflection angles due to the line heating process. Comparison of the numerical and experimental results shows the accuracy of the models.
- The FEM model was used to generate a extensive database of heatline process including optimized time of cooling, optimized time between passes or the optimal distance between heatlines. With this database was performed to develop an intelligence system of automatic forming.
- The intelligent system was used to predict the optimal sequence of heatline forming of a big dimension plate part of the hull. The system was able to predict the correct shape. The sequence was implemented on the FEM model and the result demonstrates that the sequence can be valid.
- The time of computation between both methods is not comparable because the time to estimate the sequence is one week for the FEM method and 1 minute under intelligence system. Therefore, the simplified model obtains accurate estimation of the bending angles much more efficiently.

## ACKNOWLEDGEMENTS

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