

Structural optimization of a transversal rolling mill component to improve flexional stiffness

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Abstract: The structural component investigated is a roll mill bar which sustain a plug for a transversal rolling of steel pipes. The improvement of the stiffness of this component is the target of the simulation to achieve the desired flexional displacement. An optimization tool is used to achieve the target in a proper and fast way. A 3D FEM model is developed to perform several different static analyses as basis of optimization process. The bending response of the structure is studied on the basis of the real working condition introducing the loads measured in the plant. Explicit model is then used to simulate the new stiffness in the expanding roll process.

The main purpose of the improved stiffness is to stabilize the rolling process to maintain the bar and the plug aligned with roll axis, keeping the setup of the machine.

The results of Explicit simulations suggest an effective influence of the bar stiffness on the behavior of the machine in terms of dynamic equilibrium.

Keywords: FEM, Tube Expansion, optimization, Screening Analysis, Rolling mill process stabilization.

1. Introduction

Tenaris Dalmine is a leader company for oil and gas services with the main activity in steel pipe production. To design more high end products and processes Tenaris R&D centres in the world use numerical simulation. In *TenarisDalmine* FEM (1) model are developed and used to investigate and solve some practical problem and study the mill process and product in detail. The power and flexibility of simulation gives to analysts the chance to freeze some variables and can let them focus on particular aspect of the problem. This way can isolate the phenomenon causes and find direct correlation to the process output in order to study in detail a specific solution.

Virtual simulation can reduce the costs of investigation avoiding many industrial test. In fact in the world of steel pipe manufacturing industrial tests are very expensive and very energy consuming, the industrial trials must be done only after a deep investigation with laboratory and virtual simulation to be sure to reach the target with the fewest full scale trials as possible.

A particular process of pipe production is transversal rolling. This process includes for example piercing mill (process to obtain a hollow from full section billet) , elongation mill (process to increase the length of a hollow reducing the thickness), expanding mill (Process to increase the diameter of a pipe reducing the thickness) and reeling mill (Process to improve the surface quality of the pipe). All these processes imply severe contact problem which can be sometime overcome with explicit FEM formulation.

This is a preliminary study to understand if an increased stiffness of a structural component of the transversal mill (the bar component) can bring some effects in the product by stabilizing the process. At the same time this example is a first exercise to introduce an optimization technique in our team as a standard working tool. This work analyze the bar sustaining the plug, a component of the expander mill. This component has a length of almost 20 meter, it is a cylindrical structure that sustains a conical plug where the expanding process occurs. During the expanding process a pipe heated at high temperature is deformed between two conical disks and a conical plug to increase its diameter reducing in the meantime the wall thickness. The aim of the work is to study a solution to increase the stiffness of the bar trying to keep the mill set up stable. The plug position deviates from the mill centre because of the lamination forces and gravity. The new bar stiffness can be introduced in a explicit mill simulation model to calculate the effect on plug deviation loaded by the mill forces generated by disks and plug contact.

2. Expander mill process description

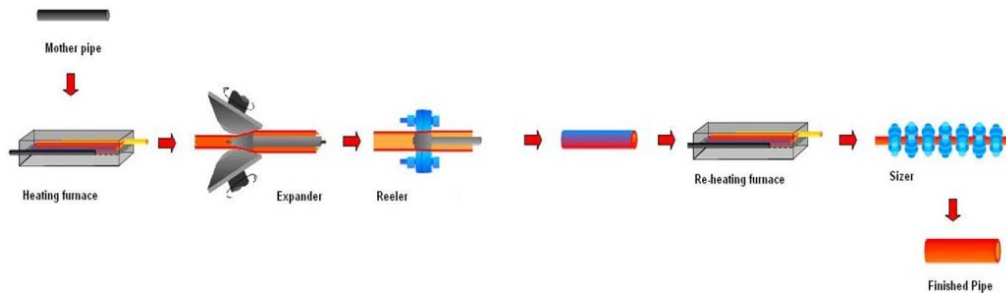


Fig.1. Rotary Expander Mill Process

The Rotary Expander Mill produces large diameter pipes (up to 28"). Figure 1 shows the process scheme. The input material is a *mother pipe*, heated to rolling temperature in a walking beam furnace, the rolling process then includes the expanding step where pipe diameter increases while reducing wall thickness and the reeling step to improve the surface quality. At this point the pipe must be reheated before the sizer machine that modifies the outer diameter to get the correct geometry of the finished pipe.

Rotary Expander is composed by

1. 2 rotating disks laying on a horizontal planes with offset and axially adjustable for set-up purposes
2. 2 fixed guide shoes (upper and lower) laying in a vertical plane and both vertically and horizontally adjustable for setting purposes.
3. 1 conical plug laying on the mill centre-line, longitudinally adjustable for set-up and process purposes, and hold in position by 4 three-rolls steadier

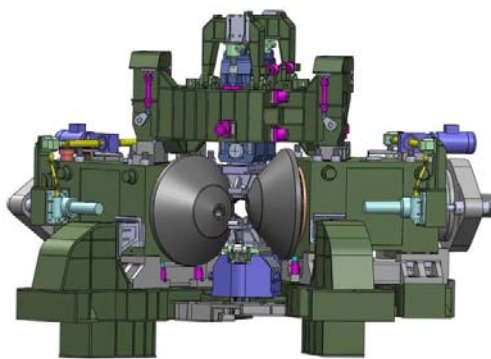


Fig.2. Rotary Expander Mill Stand

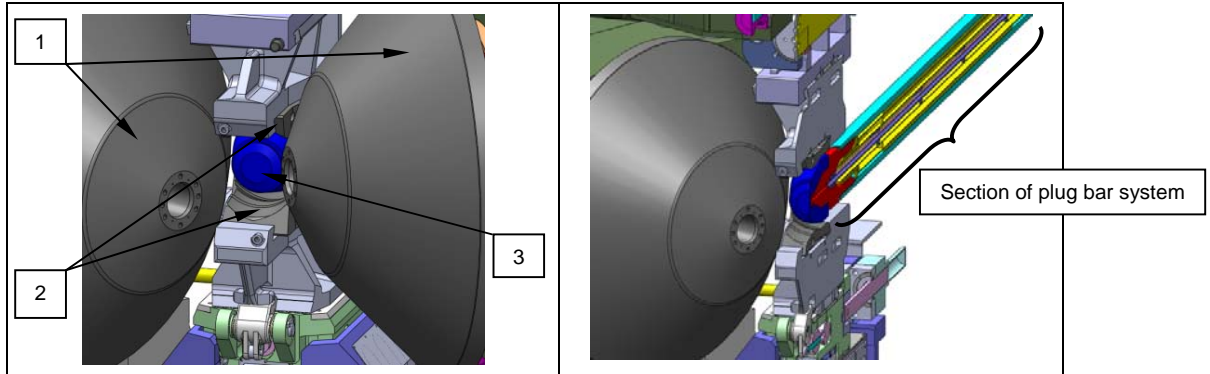


Fig.3. Rotary Expander Mill Stand (1. Disk detail, 2. Guide shoe detail, 3. Plug detail – on the right: section with plug bar system structure)

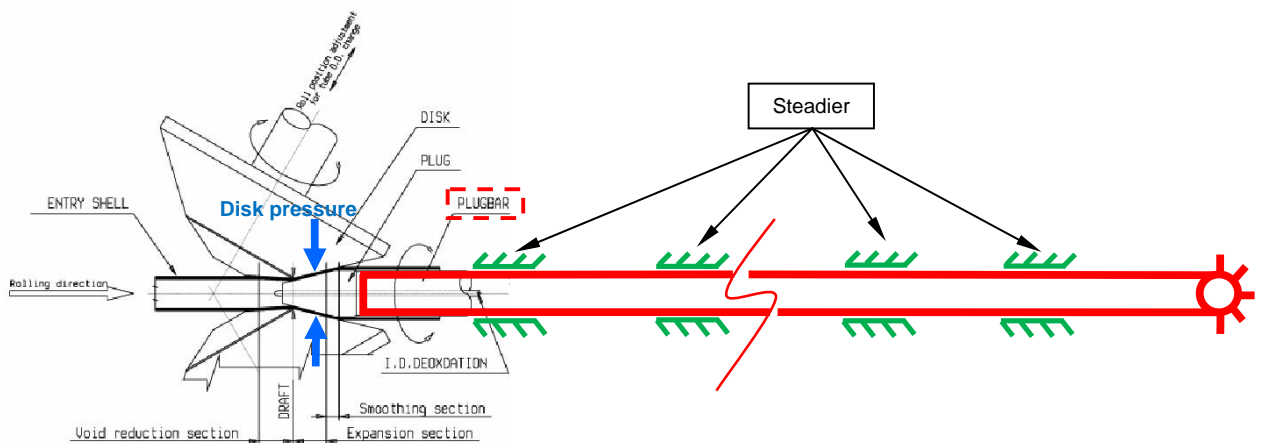


Fig.4. Rotary Expander Mill Scheme

The structure defined PLUGBAR is the main structure under investigation in this analysis. The picture in Fig.4 shows the expander mill process and the role of the plug bar. During the expanding process the conical plug is sustained by the plug bar. Both the components are kept in rotation before the contact with the pipe to reduce the effect of the rotational inertia on the contact. The bar at the beginning of rolling is constrained with four steadier (Figure 4) which allows the rotation of the bar but not the vertical and transversal displacement. As far as the process advances on the plug bar, the steadyers will sequentially open, to allow the correct passing section for the pipe, thus losing their locking function. For heavy short pipes just the first steadier opens while for long thin ones the following steadier must open. The actual study consider the bar stiffness with all the steadier closed and the release of just the first one.

3. Study of the actual bar stiffness

The first step for the comprehension of the component efficiency is to analyze the actual structure. The complete structure is more than 20 meters long. In Figure 5 bar details, the header tail and body are presented.

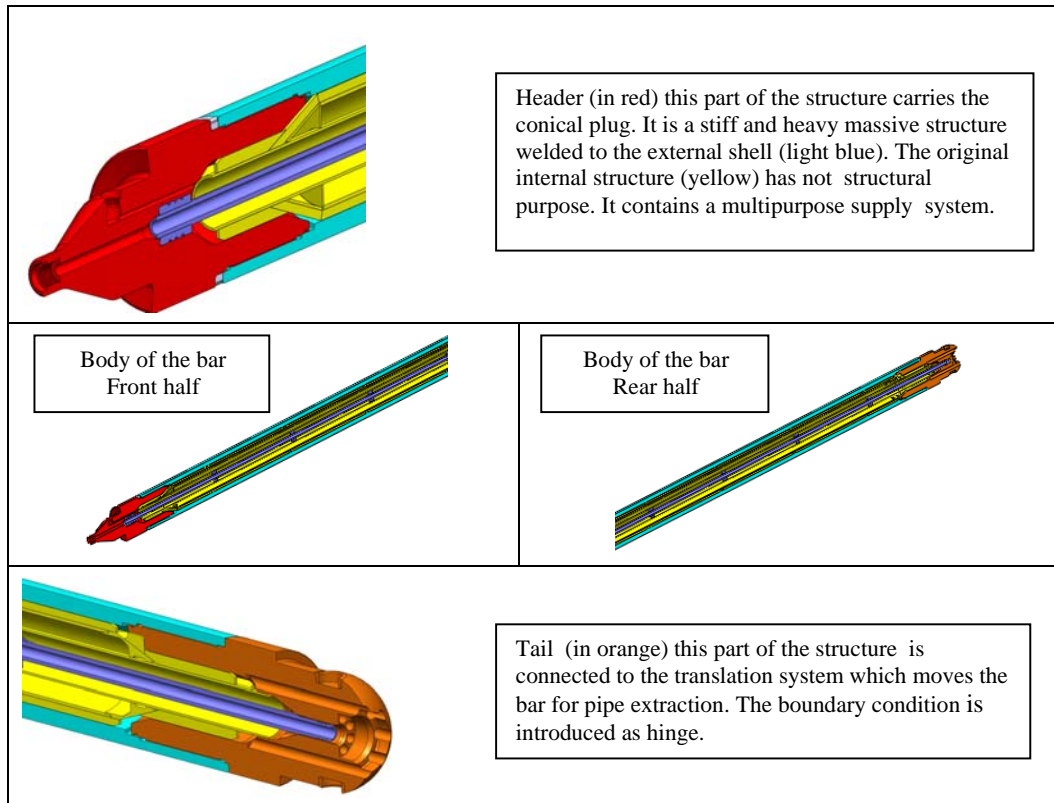


Fig.5. Plug Bar, Details.

The actual bar stiffness is related only to the outer shell pipe, which is for small outer diameter products a pipe with 340 millimetres diameter and a heavy wall thickness. Inside the pipe there is a structure which is not working together with external shell for structural stiffness. The stiffness of the outer pipe alone is not enough to react properly the laminating forces. The connection of the internal structure to the outer shell is the first try to increase the bar stiffness. In the original configuration the internal structure is just carried by the outer shell and no stiff connection are present, the first try then is to increase the working inertia for flexional stiffness. Unfortunately with this first solution it is not possible to get interesting improvements. After a first optimization analysis of this structure the results led to the conclusion that it is not sufficient to use the actual

structure to increase the stiffness in a significant way. Several gaps are present between the internal and the external structure and in reality just the external structure reacts at bending loads.

A first evaluation is made with a full section for the bar compared with a pipe section. The displacement under rolling load as a function of bar length is shown in Figure 6. If there were just the gravity load the pipe section would be more efficient than the full one but for the considered diameter of the plug bar the increase in stiffness achieved by adopting the full section leads to an improvement in displacement reduction when rolling loads overcome 5000 N (this is the value to have almost the same displacements along the bar with the first steadier open for both geometry)

In this preliminary analysis the gravity load is not considered because the rolling load is greater than 5000 N (the rolling loads are much higher) having the displacement due to gravity negligible with respect to displacement due to the rolling loads.

For the gravity and rolling load condition the full section would be the stiffer solution, but, because of a limit on the maximum weight of the total bar and because of handling purposes we must keep a solution with hollow section. The solution geometry must be in between a pipe section and a full section.

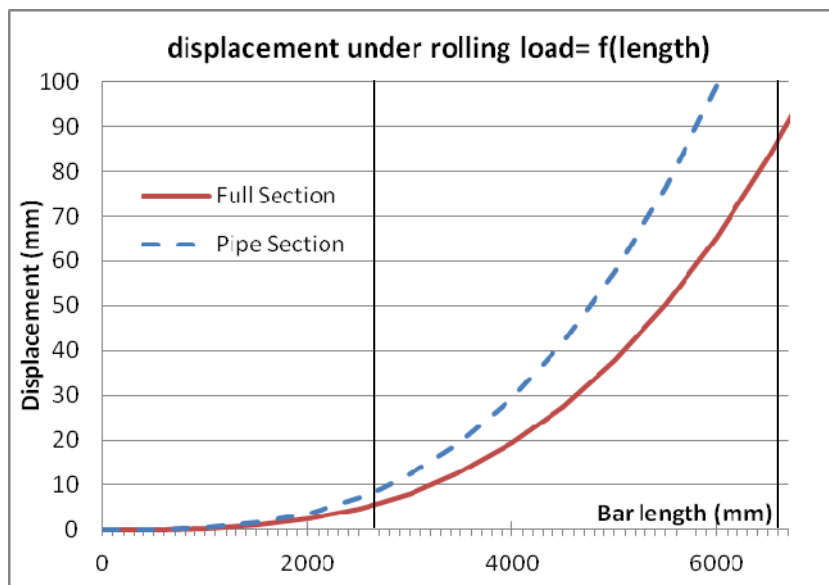


Fig.6. Flexional displacement under roll load along the bar length

A complete new design must be considered. The static model is used to calculate the displacement of the structure. Total mass is the output which must be constrained and of course displacement must be reduced as much as possible for both the condition (all steadier closed and first one open).

4. New structure proposal – Static FEM model

A new structure is proposed to increase stiffness without increasing in a significant way the weight. The prototype of the ideal structure is made by 2D shell elements to easy analyse the structure with optimization technique. For the same reason in a preliminary analysis phase it is important to contain the calculation time of the static model, to be able to use optimization technique efficiently.

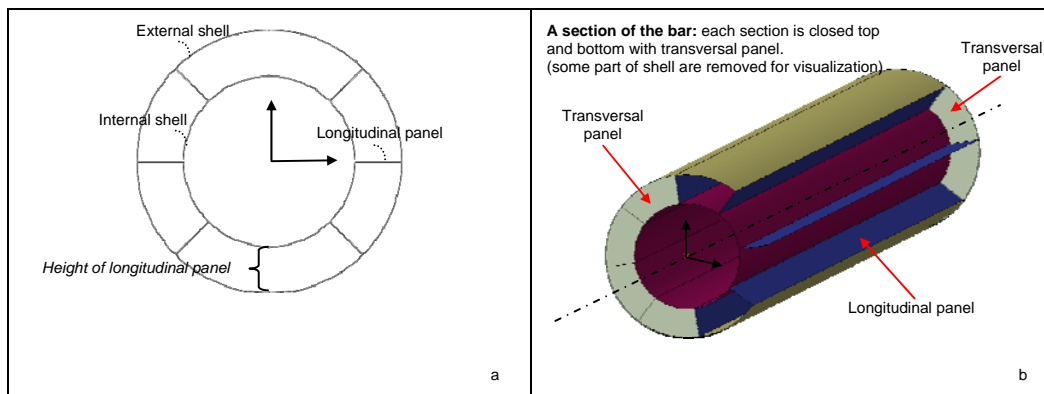


Fig.7. Plug Bar, segment of ideal structure.

The new structure studied has several connected section made by two concentric pipes and longitudinal and transversal panels to work as frame. This configuration is defined panel-frame-section structure (Figure 7 b). The model bar is then hinged at tail position and constrained at the steadier places. Gravity and a transversal load is applied at the reference point of the front tip (conical plug position) to simulate the lamination loads. Two steps are introduced for the static calculation, one with all the steadier closed and the following with the first steadier open. In the optimization scheme the variables are the thickness of the shells sections and a minimization of the lateral displacement is the target for both the steps. A constrain on the total weight is introduced for handling operations. In this first geometry the transversal section is not supposed to change to have a simple and fast model. Further investigation in the future will have to consider different geometry section introducing as optimization variable the *height of longitudinal panel* (Figure 7a) and as consequence the radius of internal shell. This could be an interesting variable to work with in the future.

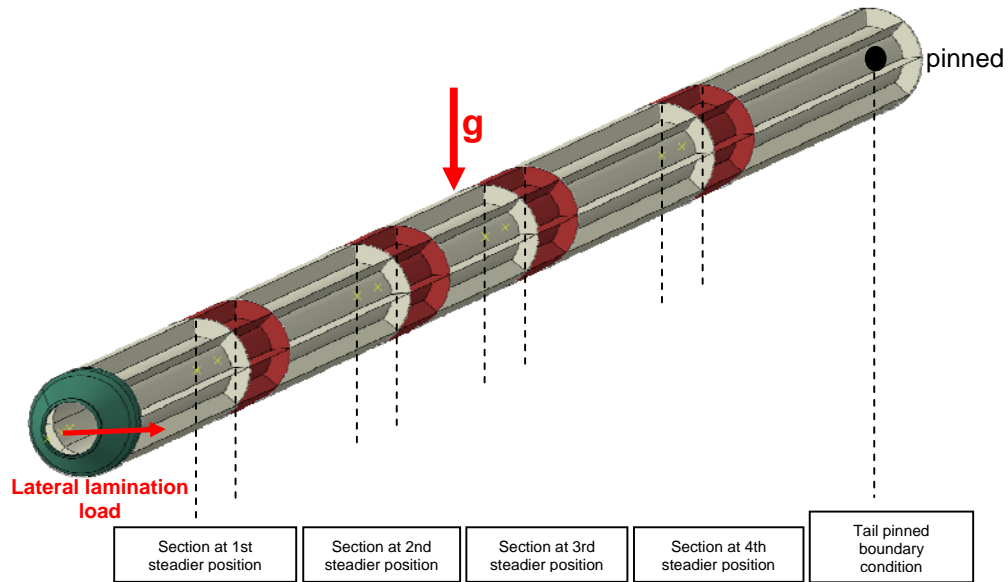


Fig.8. Plug Bar, complete ideal structure.

Figure 8 shows the scheme of the static model with load and geometry sections.

Due to the high number of variables the optimization model must identify the most important ones among all the section shell. Although structure is defined by many thicknesses only 16 section must be considered. These thicknesses are related to the front half of the structure. For heavy pipe production the third and fourth steadier remain almost always closed. Screening method and genetic algorithm is used to identify automatically the sections with important influence in flexional stiffness during the optimization. The optimization process start with random DOE (Design of Experience) and then the screening algorithm starts the analysis to find the sensitivity of each variable and at the end the genetic algorithm searches for the optimized solution. While it is easy to understand which are the sections with more influence when all the steadiers are closed the situation is not so clear when the first steadier opens, because the variables with *direct influence* in the first step have *inverse influence* in the second, due to the gravity load.

Flexional stiffness - Step static

Table 1. change of Boundary condition for steadier.

<pre> *Step, name=Expander_05 *Static 0.5, 0.5, 5e-06, 0.5 ** Name: Steadier01 *Boundary _PickedSet154, ENCASTRE ** Name: Steadier02 *Boundary _PickedSet155, ENCASTRE ** Name: Steadier03 *Boundary _PickedSet156, ENCASTRE ** Name: Steadier04 *Boundary _PickedSet157, ENCASTRE *node print ,nset=REF_LOAD_FX U , </pre>	<pre> *Step, name=Expander_05_OpenSteadier *Static 0.5, 0.5, 5e-06, 0.5 ** Name: Steadier01 *Boundary, op=NEW ** Name: Steadier02 *Boundary, op=NEW _PickedSet155, ENCASTRE ** Name: Steadier03 *Boundary, op=NEW _PickedSet156, ENCASTRE ** Name: Steadier04 *Boundary, op=NEW _PickedSet157, ENCASTRE *node print ,nset=REF_LOAD_FX U , </pre>
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Table 1 shows the change of constrain between steps: in the second step the encastre for the first steadier is released, this is the only modification.

5. Structure optimization.

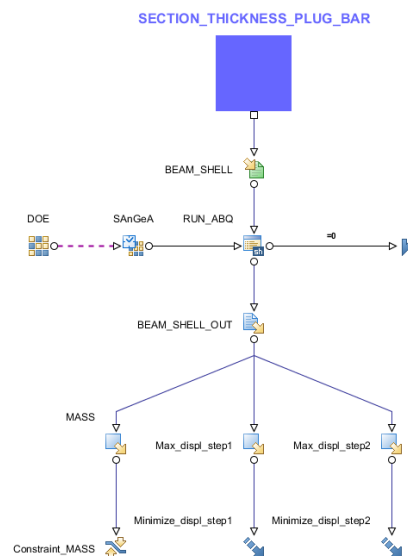


Fig.9. Workflow and optimization scheme.

Figure 9. shows the workflow for optimization analysis. The 36 section thickness are introduced in the model (SECTION_THICKNESS_PLUG_BAR). The block BEAM_SHELL introduces the FEM model while BEAM_SHELL_OUTPUT reports the displacement and the total mass as output. The last part indicates the constraint on total mass and the objectives of displacement minimization. The ideal bar is composed of 9 section and every section has 4 different thickness shell set. 36 variables are too many as input for optimization, so it is necessary to reduce the variables number. Thanks to the physic of the problem and to the constraints of the 3rd and 4th steadier the attention can be focused on the front half of the bar up to the third steadier which remains for these products always closed. The number of interesting variables can be reduced to 16. All the other input variables are kept constant. Among these 16 variables it is no more easy to understand which are the important variables because of the two different steps with different constraint. A screening analysis can be used to identify which are the variables with big influence to minimize the displacement for both the condition. As first 20 random jobs are run to populate the design of experiment. Screening analysis runs 10 job for each variable keeping one of them fixed and changing all the others. With these analysis it is possible to define the influence of each variables. After the screening phase a Genetic Algorithm (Multi Object Genetic Algorithm - MOGA II) works for the optimized solution (L.Ricco, 2011). The total optimization with 16 input variables is made then of 20 random analysis to populate the design of experiment, 160 screening analysis and 380 genetic algorithm analysis.

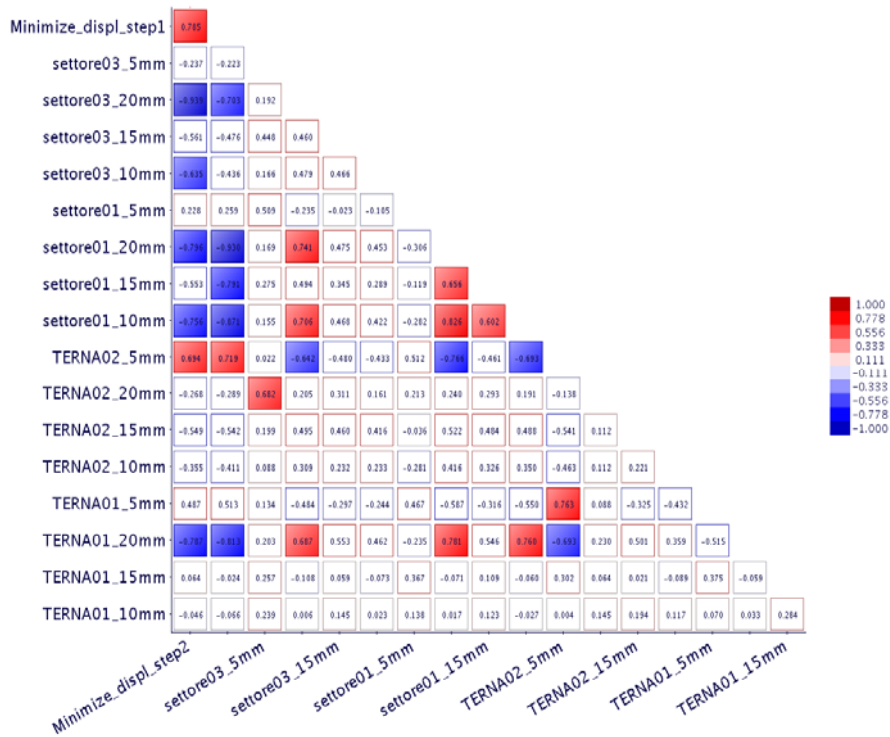


Fig.10. Correlation Matrix variables outputs

Figure 10 shows the correlation matrix between the variables in relation to the objective. The correlation is a measure of the linear association between the variables, in red the positively correlation and in blue negatively correlation. The value near to 0 indicates low correlation .

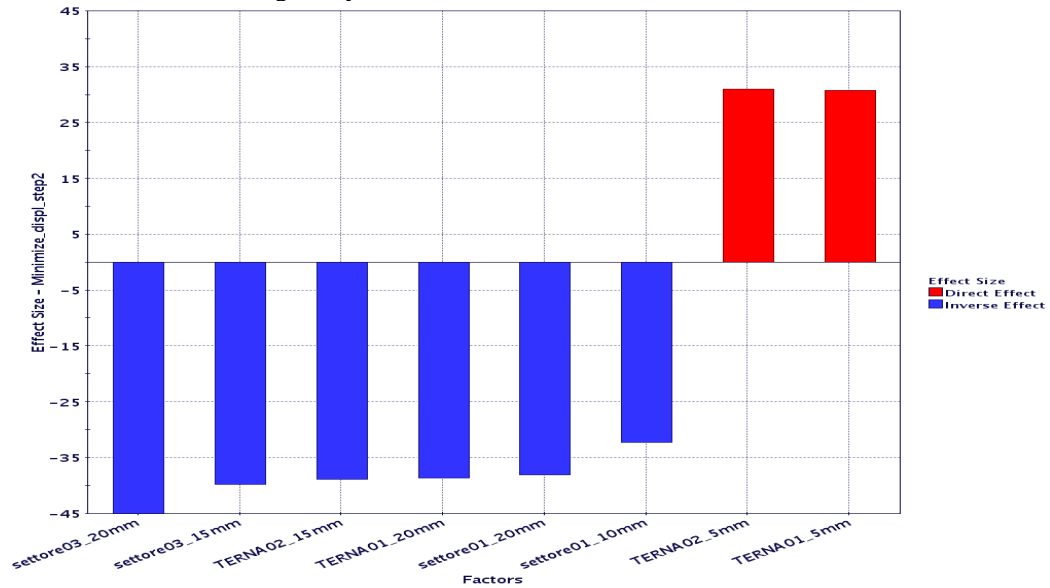


Fig.11. Effect size (Tstudent for displ2)

In Figure 11 the *Tstudent* chart can give a relationship between input and output variables. The effect size (height of the bar) gives the strength of the relationship between input and output. Color red (positive values) is for the direct correlation and blue (negative) for inverse.

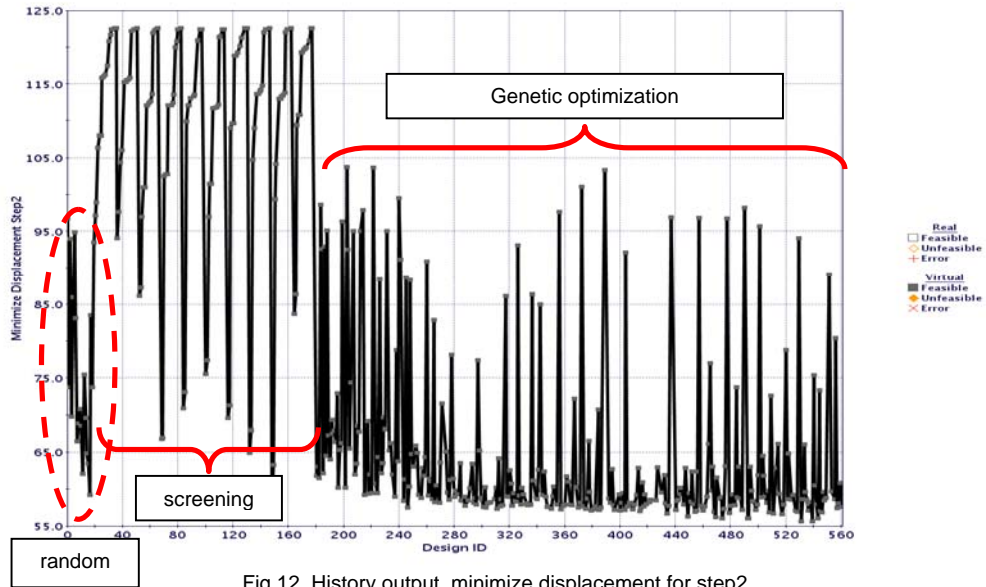


Fig.12. History output, minimize displacement for step2

Figure 12 shows the history output of the displacement for the calculation during the optimization process for all the design ID. It is possible to see the initial phase with the 20 random analysis, than the screening part and the Multi Objective Genetic Algorithm for the optimization up to ID 561.

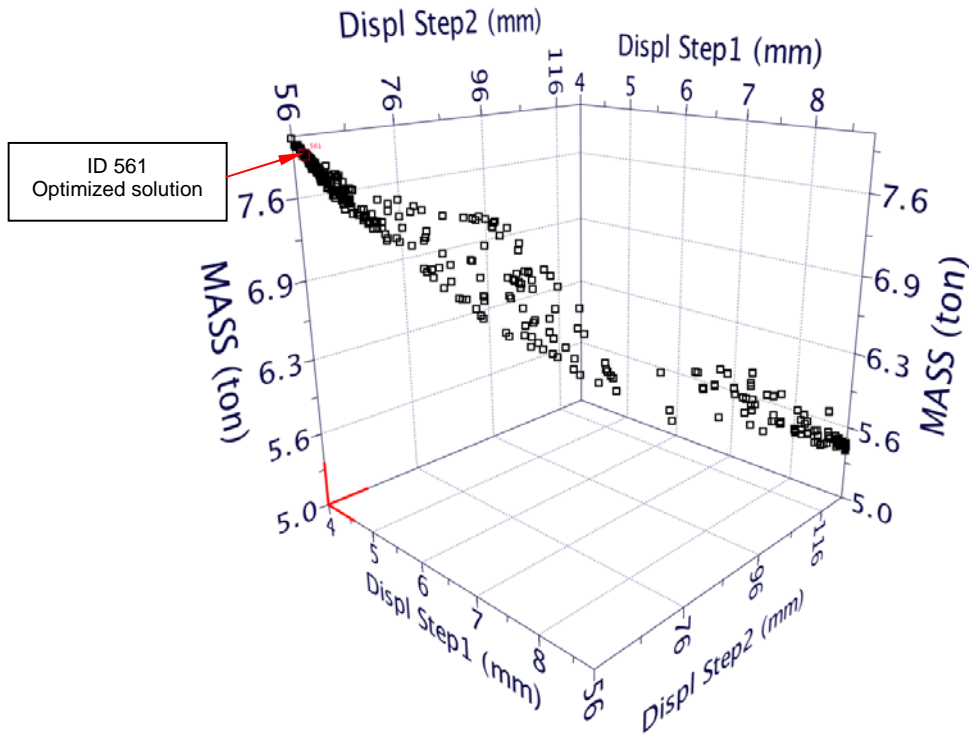


Fig.13. 3D scatter with optimized design

The optimized configuration chosen (ID 561) consider a total mass of 7,98 ton. The corresponding inertia set a stiffness with displacement of 3,9 mm for the first step and 55 mm for the second. The starting configuration had a displacement of 8,69 mm for first step and 122,6 mm for second step with a corresponding mass of 5,43 ton. The improvement for the optimized solution is around 45% in stiffness keeping the mass in the constraint range.

6. Explicit model with flexible beam – steadier constraints

Explicit Model – Dynamic Explicit

Table 2. Explicit Step for Rolling Mill

```
** STEP: expander
**
*Step, name=expander
*Dynamic, Explicit
, 6.
** Mass Scaling: Semi-Automatic
**           TUBO-1.ELEMENTS_TUBE
*Fixed Mass Scaling, elset=TUBO-1.ELEMENTS_TUBE, factor=16.
```

Table 2 reports the step for the explicit analysis. It is not possible to reduce the calculation time with high mass scaling due to the inertia effect. In this case a fixed mass scaling of 16 is used but a variable one with a target time step could be possible as well.

In Figure 14 there is a comparison between the displacement of the plug under rolling forces in different configurations. Lateral and vertical displacement with plug bar modelled as pipe section and as full bar section (1D bar model encastre steadier constraint), the optimized bar configuration is the last part of the picture. The stiffness of the bar can change the behaviour of all the mill modifying the dynamic equilibrium point in such a way that the mill centre could be aligned or not with the mill axis.

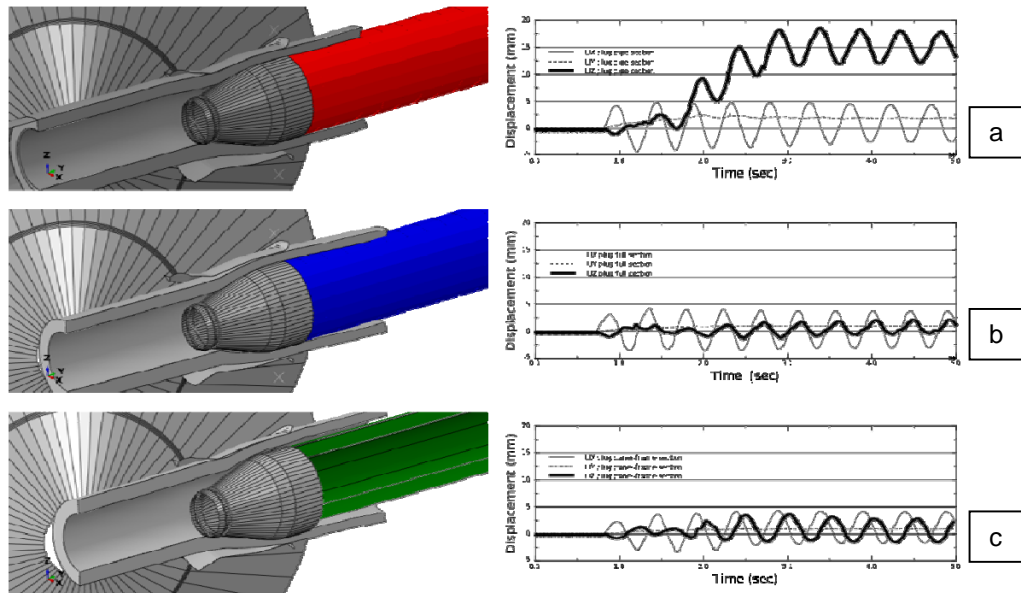


Fig.14. Displacement of plug tip under lamination forces. The stiffness of the bar sustaining the plug can change due to the cross section inertia keeping more aligned the plug-bar system.

The optimization may lead to a big improvement of the stiffness for flexion of the plug bar, the effect in the mill can be interesting for the influence on dynamic equilibrium. In Figure 14 it is possible to appreciate the difference of the bar stiffness in the mill. Figure 14a shows the displacement of the reference point of the conical plug if the bar is modeled as a heavy wall pipe. The solution with a full section for the bar is shown in figure 14b while the displacement resulted in fig 14c is related to the *panel-frame-section* with the thickness obtained from optimization, as a very interesting results this last solution is aligned with the full section structure solution, leading to an optimum compromise between weight and stiffness of the plugbar.

ACKNOWLEDGEMENTS

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7. References

1. Abaqus V11.1, Dassault Systems SIMULIA Corp. Providence, RI, USA (2010)
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