CLECIM® Laser Welding Machines
Finding the optimal parameters for laser welding of steel plates with JMP

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Purpose – To be considered good, a weld bead must meet two criteria: it must be free of defects (such as spatter, humpings, underfill, holes, etc.) and resistant (assessed by means of an Erichsen-type cupping test). The search for the optimal parameters for laser welding steel plates is already extremely demanding due to this double constraint. But if, on the top of that, you consider the productivity of the processing line and the quality of the incoming material, then the task becomes a challenge!
Approach – And that is precisely this challenge that was overcome with the use of JMP. To achieve this result, many steps were implemented, all of them requiring the use of a JMP platform or feature:
1) Base material strength analysis, qualification of the two plates to be welded *[Graph builder, Map shape, ANOVA, Dashboard]*
2) Synthesis of the visual observations, production of the weld defects map, which determines a study area of irregular shape where the weld seam is flawless. *[Graph builder, Multiple pictures hover label]*
3) Weld strength analysis and optimization on a non-homogeneous material and on the defined defect-free zone, given as a set of candidate points. *[Custom design, Split-plot, Covariates, Uncontrolled factor, Fit model, Prediction and Contour profilers]*
Findings and Value – For the given material, the objective was achieved since all the steps allowed to propose and validate a set point with a maximum productivity and a good weld, both defect-free and resistant, JMP being pliable and able to adapt to all the constraints of the process and the material.

Key words: JMP, laser welding, design of experiments, DoE, covariates, LW21M, LW21H

1. Background and introduction

Steel strip manufacturing ever reinvents itself by propositing new metallurgical concepts, requiring to tackle technical limitations of production systems. As a provider of mechatronic solutions for steel plate processing, Clecim SAS recently expanded its laser welder line with a next-generation machine capable of cutting and welding heavy plate using a 12kW laser source. Addressing the usual drawbacks in maintenance, operation and safety of current welding system based on mechanical cutting and CO_2 laser welding, the newly developped LW21H (Heavy) welding machine benefits from a smarter approach by processing thicker strips up to 9 mm with solid-state laser cutting and welding. This new generation of welders, heir to Clecim SAS' 20 years of experience in welding and in particular its little sister - the LW21M (Medium) - pushes back the current limits of performance and technological drawbacks observed in solutions for thicker materials. It is materialized by a 1:1 scale pilot designed, manufactured and tested in Clecim SAS workshops ➲ **Figure 1**.

In 2019, the laser cutting process was extensively studied and the use of Machine Learning techniques allowed for the conception of a model able of delivering robust cutting presets across the thickness range. Today, the focus is on the laser welding process and the acquisition of high-quality data that will soon allow the creation of a welding model, the final step for a completely automated machine. To achieve a good weld, two criteria must be met: a weld seam free of defects (such as spatters, droplets, etc.), and a good strength. To reach this result on a given material, many steps have been followed:

- The determination of the welding flaws map and the weldability lobe, area where the weld seam is defect-free
- The determination of the base material strength to ensure that the pieces of material are identical and homogenous
- The analysis and modeling, via a DoE of the weld seam strength on the previously determined weldability lobe, which usually has a highly irregular shape

Let's now dive into the details of these exciting steps, all of them requiring the use of a JMP platform.

Figure 1 – Heavy laser welder at Montbrison workshop
The upper picture presents an external view of the welder containment. The size of the door gives an idea of the dimensions of this industrial welder. The lower picture presents a partial view of the inner part of the machine. Head and tail of the two plates will be cut by laser technology and then welded together.

Notation

M	Material type	*F*	Focusing distance
H	Material thickness	*G*	Gap between the plates
P	Laser power	*T*	Thermal treatment
V	Travel speed of the welding carriage		

2. Laser welding process and factors

The welding process is made of 3 parts: the two plates to be welded which can be of the same nature and thickness or not, the laser welding head mounted onto a travelling carriage and connected to its 12kW laser source. To give an idea of the delivered power, a classic laser pointer used for a presentation has typically a power of 1mW. In comparison, the laser source used by Clecim SAS to cut and weld the pieces of material is 12 million times more powerful.

Generally speaking, the influencing parameters of laser welding belong to two categories, namely those related to the material to be welded itself, such as its nature *M* and thickness *H*, and those related to the process, such as the laser power used *P*, the speed of the welding carriage *V*, the focusing distance *F*, the heat treatment *T* or the spacing between the sheets *G*. To a lesser degree, other parameters are involved such as the inclination of the laser welding head, the type of shielding gas, its pressure, etc. Within the framework of this paper, only the used laser power *P* and travel speed of the welding carriage *V* will be considered. The materials to be welded will be identical and of the same thickness.

To put it in a nutshell, for the given pieces of material (M, H), two factors (P, V) have to be optimized with the goal of getting a flawless and resistant weld seam.

3. Weldability lobe

The first step of the experimental approach consists in performing tests in order to build a map of welding defects and thus determine the weldability zone, i.e. the defect-free zone. Depending on the thickness of the material, the number of tests to perform can quickly become important. In effect, the goal is to test all the pairs (P, V) and to visually observe the quality of the weld bead to know if the combination (P, V) generates a defect or not. In order to drastically reduce the number of tests and to save time, the so-called “power jumps” procedure is used. In a single trial, at fixed speed, 11 power jumps, from 2 to 12kW in 1kW steps, are carried out giving the possibility to perform 11 tests in one. Regarding the welding speed, steps of 2 m/min were used from 3 to 18 m/min. In the end, the upper and lower parts of 88 weld seams were visually inspected and qualified.

The results were stored in a JMP table and evaluated using the Graph Builder platform ➲ **Figure 2**. The welding speed *V* is shown on the x-axis and the used laser power *P* on the y-axis. For a given speed, we find the 11 visual observations corresponding to the 11 power jumps of the test protocol. Thanks to the association of a color and a shape, in one combined, it is possible to represent four welding flaws at the same time and to visualize hence the major defect areas in this way. For each pair (P, V), pictures from the top and bottom weld seam have also been taken and stored into two expression/vector columns so that they can simultaneously appear in the tooltip area. By moving the mouse over the points, the pictures are displayed. This functionality allows to easily compare the influence of a factor change on the weld bead facies and thus to progressively enter into the understanding of the laser welding process.

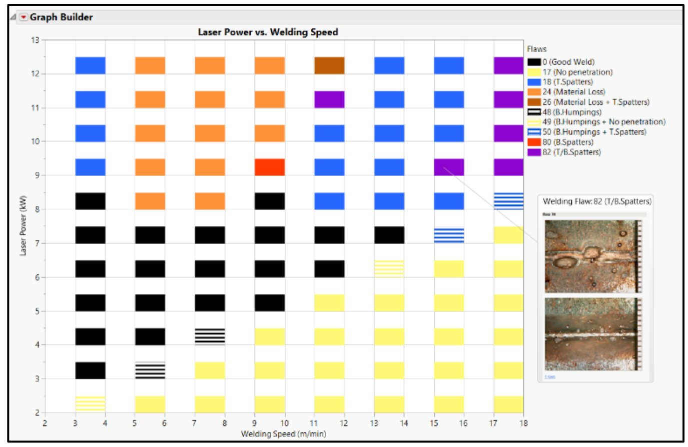

Figure 2 – Welding flaws map
JMP Chart Builder is used to view the weld defect map. The major defect areas can easily be recognized: partial penetration (yellow), holes (orange), spatters (blue, purple), chain of pearls (horizontale stripes), defect-free area (black). Pictures of the top and bottom weld seam are displayed in the tooltip area when moving the mouse over.

4. Base material strength analysis

Before going further in the analysis of the welds, it is necessary to evaluate the strength of the base material, and this for 3 reasons:

- The first reason is to establish a reference strength so that we can make comparisons.
- The second one is to make sure that the 2 plates sent to us by our customer are comparable.
- And the third one is to make sure that the plates are homogeneous and that they do not have any resistance profile in their width for instance.

To do that, Erichsen-type cupping tests on plates without any welds. Stamping is done via a ball and the breakage resistance is automatically recorded. The protocol provides for three measurements in the width of the plate. Positions are respectively DS (drive side of the welding machine), C (center) and OS (operator side). The various results are stored in a JMP table and summarized in a dashboard ➲ **Figure 3**.

In summary, the two plates to be welded can be considered identical, but further investigations are needed to understand why the strength variance is higher on the operator side.

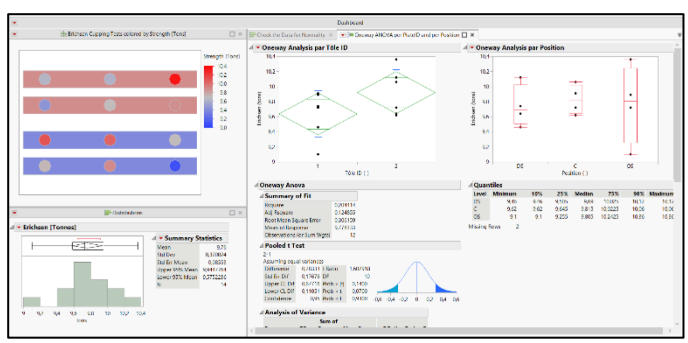

Figure 3 – Base material strength analysis
The dashboard is composed of various JMP platforms: Graph Builder, Distributions and ANOVA. The custom map shape[1] of the Graph Builder displays the two samples corresponding to each of the two plates and the position of the various cupping tests colored by strength. In the ANOVA, the overlap of the two diamond tips demonstrates that the plate can be considered as identical. The chart on the right shows that the strength variance is higher on operator side (OS). Once aggregated, data from the bottom distribution presents an average strength is 9.76±0.18 tons (at 2σ).

To understand the differences in resistance on the operator side, it is necessary to pay attention to the visual aspect of the plate ➲ **Figure 4**. Due to potential force variations during its treatment, the plates are inhomogeneous in term of strength in their width and length.

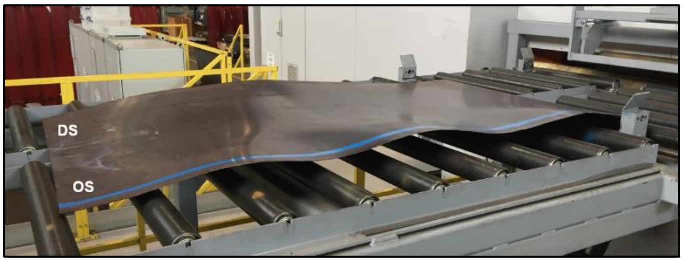

Figure 4 – Appearance of the plate
The plates present a relatively flat aspect on the drive side and waves on the operator side. The history of the plates is unknown but there must have been a rolling of planishing issue with a higher force applied on the operator side, which created this appearance and a periodic modification of the strength.

4. Weld bead strength analysis

the construction of the test plan requires taking into account all the various constraints, 4 in number:

- The first constraint is related to the irregularly shaped region[4-Ch.5] of the weldability lobe. The traditional way to do it would be to delimit the study area using multiple linear constraints. Although possible, it is the technique of the candidate points, also called covariates[2,3,4-Ch.9] in JMP, that has been chosen for the simplicity sake.
- The second one, due to the plate inhomogeneity, is related to the strength changes in the width. To take this effect into account, a 3 levels (DS, C, OS) categorical parameter is envisaged.
- The third one, also due to plate inhomogeneity, is related to the periodic and incurred strength changes in the length. This parameter cannot be controlled but it must nevertheless be considered in the future test plan.
- Finaly, the fourth one is related to the fact that the 3 values of the categorical parameter are not independent since they belong to the same treatment (i.e. weld). Subsequently, a split-plot design[4-Ch.10] with parameters hard or easy to change has to be considered.

The creation of the custom design of experiments is explained in ➲ **Figure 5**. A total of 8 tests and 24 measurements is lastly considered. The test plan is executed and for each triplet (P, V, Side) the following data are recorded: the position of the weld (in mm, from one end of the plate), the value of the strength (in absolute and in percent of the base material strength). The strength of the welds is then modeled using the Fit Model platform ➲ **Figure 6**.

The resulting model being of good quality, it can be used in prediction. After correcting for the effects of weld position and sides, the trends attributable to laser power and traveling speed are clearly visible in the Prediction Profiler ➲ **Figure 7**. For the considered material, there does not seem to be any interaction between the laser power and the welding speed. The weld strength therefore increases with the travelling speed and when the laser power decreases.

However, that being said, the work is not over yet. The limits of the weldability lobe must also be carefully considered in the search for an optimum. On the basis of the Prediction Profiler alone, this is not easy, so it is the Contour Profiler's turn to play!

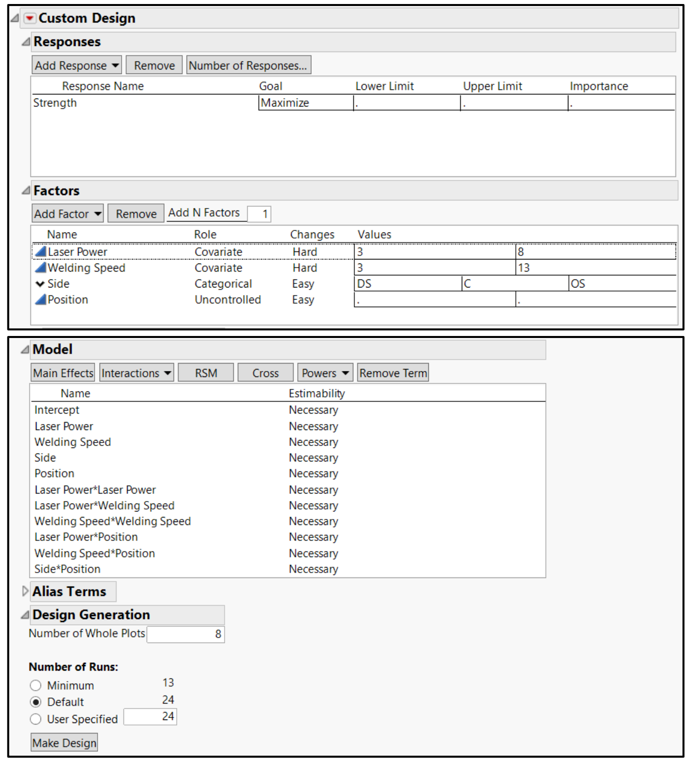

Figure 5 – Building of the custom design of experiments
The Custom Design platform allows the creation of a completely customized test plan. The Responses part provides the list of responses to be optimized, in this case the goal is to look for the maximum strength. The Factors part presents the way how the four constraints have been addressed. As the position is uncontrolled, no values are input into the limits. The Model part displays all the factors and interactions considered in the model. RSM (Response Surface Methodology) is used, the interactions between the laser power, the welding speed and the side have been removed as they have been considered not significant. Finally, the Design Generation part proposes 8 trials and 24 measurements.

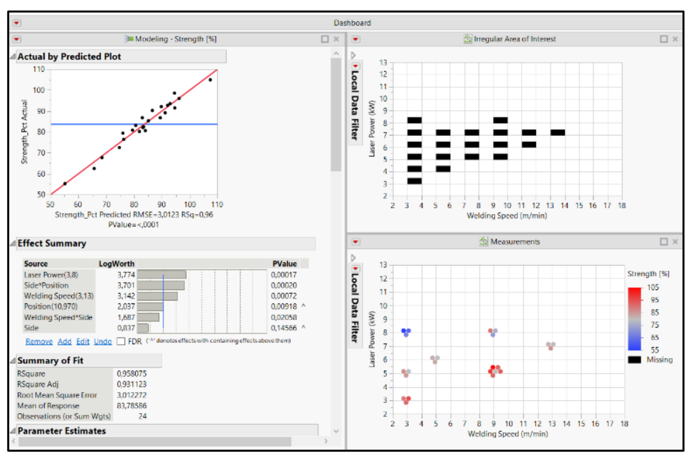

Figure 6 – Building of the custom design of experiments
The results are presented into a dashboard. The irregular shape of the weldability lobe is reminded in the top right chart. The experimental points, proposed by the Custom Design platform, and the associated strength values, in percent, are summarized in the bottom right chart. Finally, the Fit Model platform on the left displays the modeling result. An explicative power R^2 of 96% has been reached, meaning that only 4% of the variations escape its predictive power. The Effect Summary shows that the main effects (laser power, welding speed and position) are significant. The side factor is not directly significant, but becomes so when associated with the position. The VIFs (Variance Inflation Factors, not displayed here) have all a value smaller than 1.6, showing no multicolinearity issue (no linear relationship among two or more explanatory variables exists).

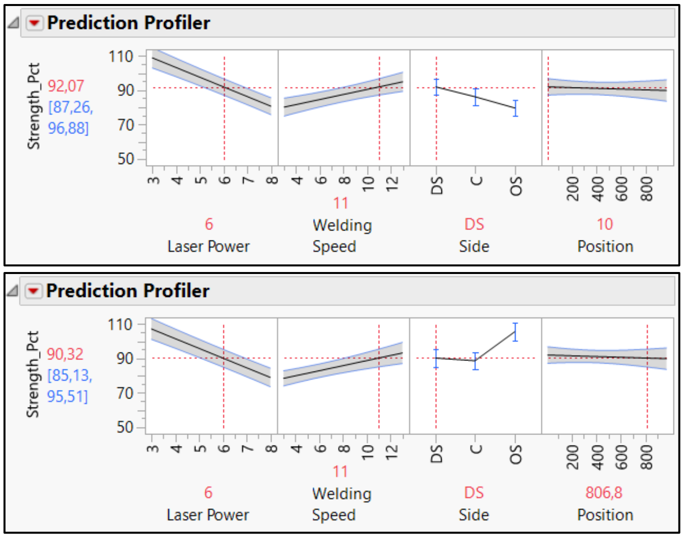

Figure 7 – Checking the model's behavior with the Profiler

The upper profiler refers to low position values, the lower to high position values. The model response (strength in %) is shown on the y-axis, the factors on the x-axis. Weld after weld (increasing position), the strengthes on the DS and C sides remain mostly unchanged while the strength on the OS side changes dramatically, as observed visually. This phenomenon being well modeled, it is now possible to access the pure effects of laser power and welding speed. The weld strength increases when the laser power decreases and the traveling speed increases.

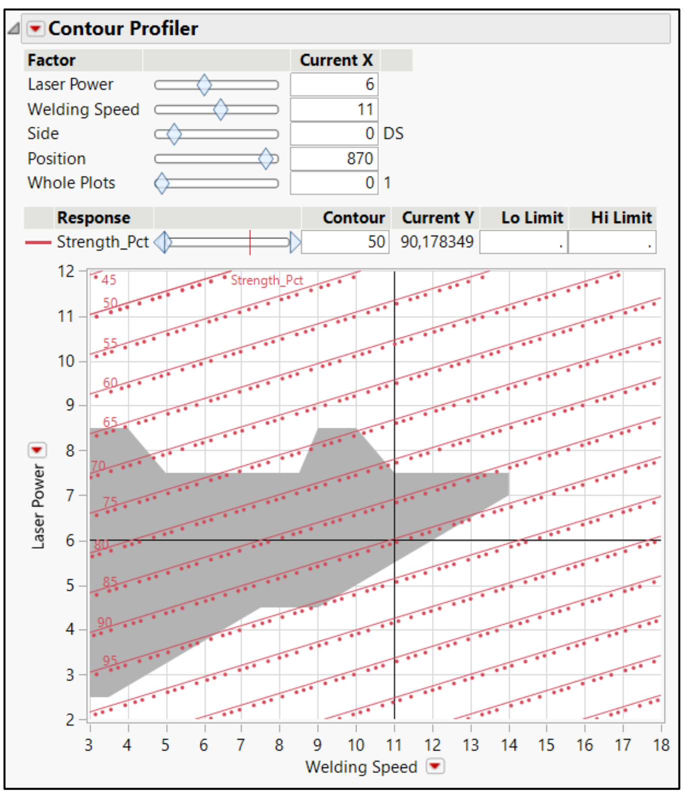

Figure 8 – Optimization with the Contour Profiler

The Contour Profiler displays the welding speed on the x-axis and the laser power on the y-axis, with the position and side values fixed. Arbitrarily, the side value was set to DS. As for the position, it was set to the latter. The weldability lobe where the weld bead is free of defects was reproduced in black using a script and the polygon drawing function.The iso-resistance curves of the model, in red, are also plotted. The associated resistance percentages are also displayed in red. The welding speed and laser power sliders are set to the coordinates of the optimal point, materialized by the black cross in the center of the graph.

The use of the Contour Profiler allows to superimpose the iso-resistance curves from the strength model with the weldability lobe ➲ **Figure 8**. Finding the optimal point requires locating a point that is not only within the weldability lobe but that also has the highest strength. If we add to this the fact that the welding speed should be as fast as possible for a maximum productivity, the coordinate spot (11 mpm, 6kW) proves to be ideal. Not only does it meet all the above criteria, but it also offers a satisfactory safety margin for an industrial process.

Of course, these settings have been tested. The results are presented ➲ **Figure 9** and ➲ **Figure 10**. In summary, the weld seam has a defect-free surface with a strength across the entire width comparable to that of the base material. The objective has been achieved!

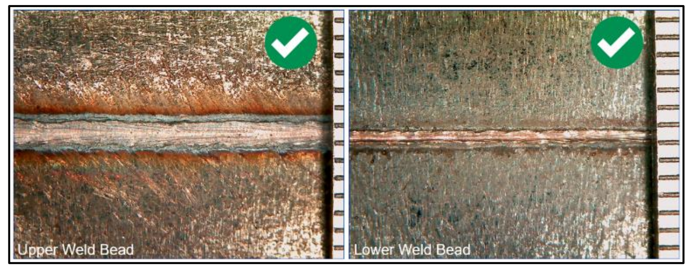

Figure 9 – Optimum preset and weld seam appearance

The figure shows the upper (left) and lower (right) weld bead facies. The latter are free of the main welding defects.

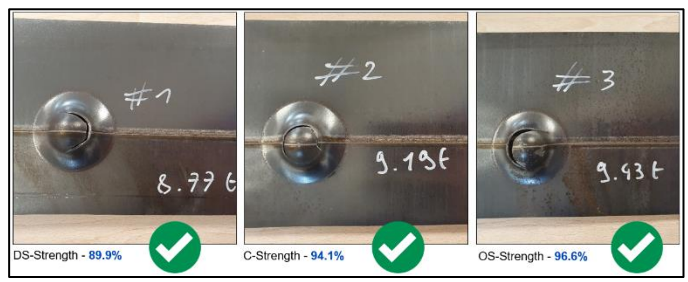

Figure 10 – Optimum preset and weld strength

The figure shows the results of the 3 Erichsen-type cupping tests performed on the DS, C and OS sides. Visually, it can be seen that it is the material that breaks and not the weld. Moreover, all the tests show a strength level comparable to the base material one.

5. Conclusion

Finding the optimal laser welding parameters for a given material is not easy. Fortunately, JMP offers a suite of platforms that, in one combined, provide a rigorous approach to achieving our goal.

The use of the Graph Builder, Personal Map Shape and Dashboards allowed us to visually organize our data both in terms of welding defects (welding flaws map, weldability lobe) and strength (Erichsen-type cupping tests).

The ANOVA and Distribution platforms were used to make informed decisions about the equivalence of the plates to be processed and their level of strength.

Once the weldability zone was determined (zone where the weld beads are free of defects), the strength of the weld bead was studied using the design of experiments methodology. In this paper, only 2 parameters were considered (laser power, welding speed).

The Custom Design platform allowed for a high degree of customization of the tests in relation to the encountered constraints. The highly irregular shape of the study area gave the opportunity to use the candidate point method (covariates), in addition to other features such as split-plot design and uncontrolled factors.

The modeling of the weld strength via the Fit Model platform allowed not only to understand the involved physical phenomena but also to proceed to a multi-criteria optimization via the Contour Profiler. Finally, the objective was achieved since all the steps allowed to propose and validate a set point with a maximum productivity and a good weld, both defect-free and resistant.

This step is part of an extensive, very high-value data acquisition program that will allow, just as it did in 2019 with the laser cutting process, the development of a laser welding model that will provide robust welding instructions, regardless of the incoming product, the final step to fully automate the machine.

6. About Clecim SAS

Clecim SAS, based in Montbrison (Loire), joined the Mutares group on April 1, 2021. It is an engineering and production company, bringing its expertise in services and manufacturing in particular for the metallurgical industry. Its main activity is the operational support of the performance of its flat steel producer customers, in particular for the automotive market. This support takes the form of studies and advice on the improvement of their production tools, the supply of special machines to optimize performance and, if necessary, the supply of complete production lines based on the latest technologies.

For decades, Clecim SAS has been promoting innovation in the steel industry and is constantly looking for new solutions to provide metal producers with state-of-the-art equipment, allowing them to gain a competitive advantage. Our latest areas of focus include new technologically differentiated solutions, advanced process analysis and optimization. Of particular note in this area are world-renowned high-level solutions such as special laser welding machines, surface inspection systems, rolling equipment, and galvanizing lines for flat steel for the automotive market.

With its own factory, Clecim SAS is able to manufacture and test complete machines. The company has many skills (engineering, manufacturing, testing) allowing it to master the entire value chain. Clecim SAS can also provide its customers with a pilot rolling mill for the development and confirmation of flattening, rolling and tribology models.

Figure 11 – Clecim SAS (Montbrison city, France)

About the author

Graduated from Grenoble INP in Materials Science and Process Engineering, Stéphane GEORGES (47y) joined Clecim SAS in 2001. After holding several positions in the Automation, Modeling and Process Control department, and after 3 years of expatriation in Erlangen at Siemens in Germany, Stéphane moved to the position of R&D Project Manager. His various missions related to industrial processes lead him to use his skills in smart experimentation, statistical analysis and modeling, coding, machine learning and deep learning to make the most of data.

Contact

To contact the author, please scan the QR Code opposite.

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Acknowledgment

We would like to express our thanks and gratitude to Florence Kussener of JMP for her support in using the software and preparing us for our first ever participation in the Discovery Summit.

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