Evolution of computer simulation and optimization with potential for machine learning and artificial intelligence

Wenqi Zhang
SWANTEC Software and Engineering ApS, Denmark
wz@swantec.com

Abstract

This paper summarizes the latest developments on numerical simulation and optimization of resistance welding and mechanical joining. Numerical simulations and optimizations have been applied for solving design-oriented problems by modeling welding combinations of geometric shape and dimensions in various materials. With increasing accuracy and integration of engineering expertise, they are also applied more and more for solving production-oriented problems by optimizations and planning of welding process parameters. Weld quality can be modelled in terms of microstructural phase changes, resulting hardness distribution and weld strengths under different loading conditions. New developments are further moving towards interaction with welding control by machine learning and artificial intelligence (AI).

1. Introduction

Numerical simulations have been widely applied in nearly all engineering fields for saving time, reducing costs, improving product quality and inspiring innovations.

The general applications of numerical simulations have first started with structural modeling for computer aided design. With increasing accuracy of process simulations and especially integration with engineering expertise, numerical simulations are more and more applied for optimization of manufacturing processes thereby getting into computer aided manufacturing.

In the past three decades, dedicated simulation software has gained more applications in simulation and optimization of welding and joining processes [1-4]. It has helped engineers to make better product design, get optimized welding processes and find the root cause of welding problems.

The welding problems that are bothering the welding engineers and designers every day can be summarized into the following three categories:

1) Design related problems due to geometric dimensions and choice of materials.
2) Production related problems due to poor settings or less optimized welding parameters.
3) Control related problems due to lack of dynamic response to process disturbances.

Numerical simulations have been widely used for solving design related problems. But, it needs much more knowledge and engineering expertise to apply numerical simulations for solving production related problems. It is even more demanding for solving the control related problems with numerical simulations, which could be feasible in the near future with the potential of interaction by machine learning and artificial intelligence (AI).

SORPAS is a dedicated welding software system with many advanced functions of numerical simulations and optimizations for solving design-related problems and production-related problems. It is developing further into a more advanced system towards control-related applications by introducing new functions to interact with the welding controls. Fig. 1 shows the software system of SORPAS.
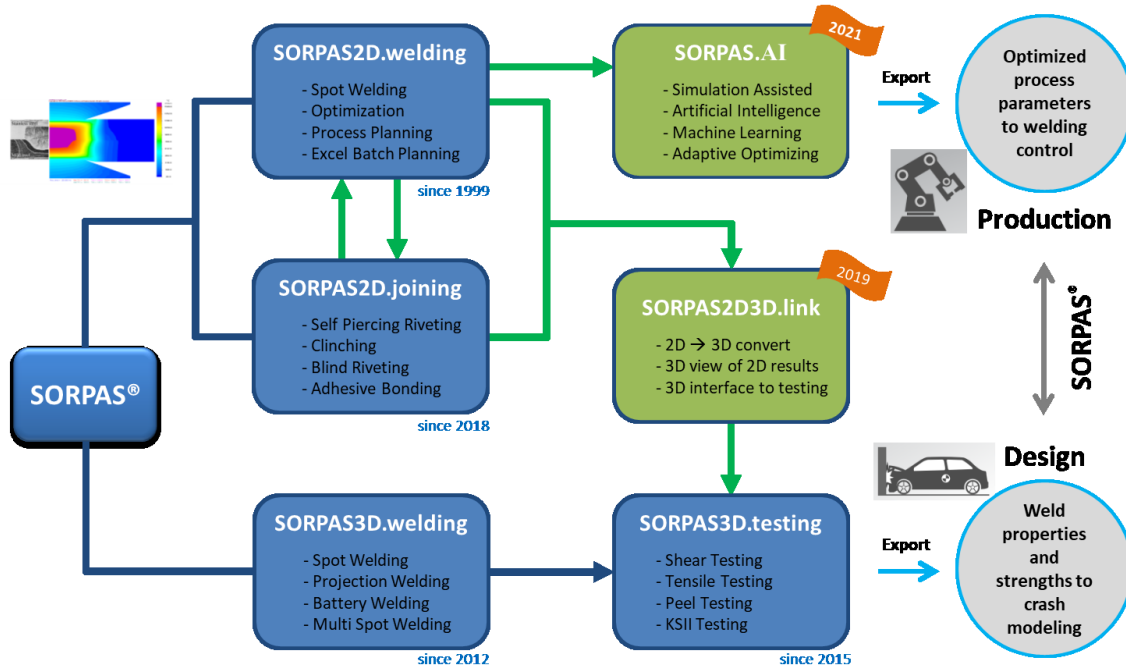

Fig. 1: The software system of SORPAS with released modules and new developments.

In this paper, we will present our latest research and development in numerical simulations and optimizations with SORPAS on the following three aspects:

- Design-oriented simulation and optimization.
- Production-oriented simulation and optimization.
- Control-oriented optimization with machine learning and artificial intelligence (AI).

2. Design-Oriented Simulation and Optimization

Many welding problems are caused by design factors including the geometric dimensions of the parts to be welded, the combination of materials and the local design of the weld contacts. Below are some examples of numerical simulations and optimizations for solving design related problems.

2.1 Design of workpieces (products)

In spot welding, different combination of sheet thickness and materials would make the welding process totally different, which also require different welding parameters. The thickness ratio and strength ratio of the sheets are important to indicate the difficulty of the welds. Fig. 2 shows eight examples of spot welding of three sheets with a thin low carbon steel sheet and two thicker sheets of higher strength steels. Each case needs different welding parameters but all showed difficulties in obtaining weld nugget into the thin low carbon steel sheet, [5].
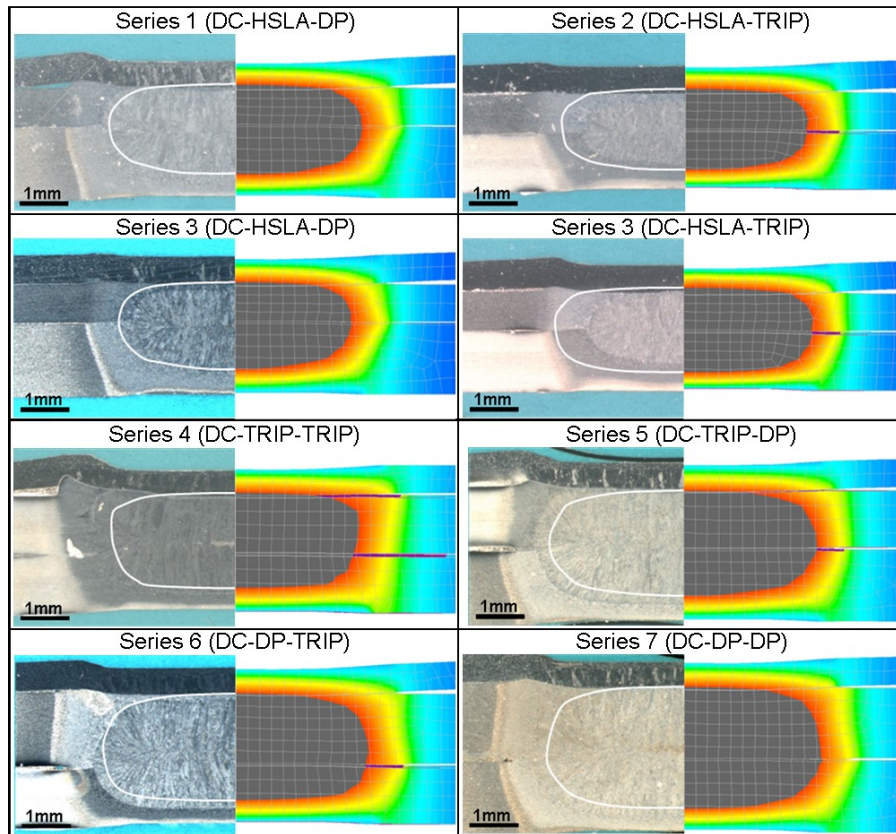
Fig. 2: Spot welding of 3-sheet with different thickness and steels simulated with SORPAS 2D [5].

In special cases of spot welding, it is only possible to access the weld location from one side due to the geometry of parts to be welded. Fig. 3 shows an example of 3D simulation of single-sided spot welding of sheet to tube. The welding process is particularly challenging due to elastic deflection of the tube and its interaction to the thickness and strength of the sheet.
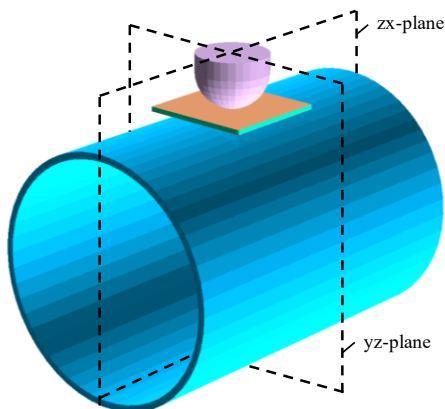
(a) 3D model for welding sheet to tube.
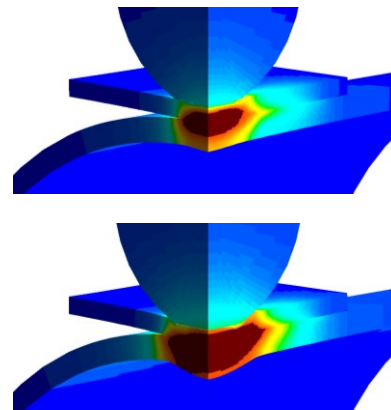
(b) Simulation results for welding sheet to tube.

Fig. 3: 3D simulation of single-sided welding of sheet to tube.

In projection welding, the design of the local weld projection could determine whether the weld can be successfully made. The local projection is needed for concentrating the current to heat up the weld interface, but it shall be deformed during the welding to get sufficient weld size. It needs optimizations to achieve the best projection design. Numerical simulations can save a lot of costs to make the virtual welding tests on the computer by screening out the bad designs

before making real parts for physical experimental tests. Fig. 4 shows the simulation of projection welding with a vertical sheet welding to a flat sheet with long embossment.
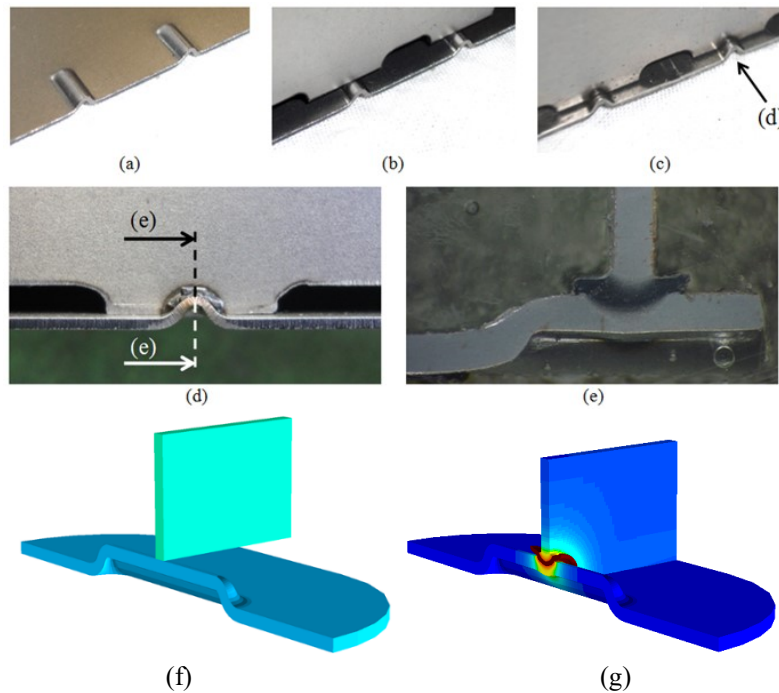

Fig. 4: Projection welding of vertical sheet to sheet with long embossment simulated by SORPAS 3D.

In electrical and electronics products, many welds are directly made between the parts by utilizing the shape of the parts. In such cases, the design of the parts especially at the weld contact is very important. With support of simulations, it is possible to test and evaluate the welding results with each design of the parts and then select the best design. It is even easier to simulate with the same geometric design but different materials for each part and then select the best material. Fig. 5 shows a micro welding example to join a wire to electrical connector.
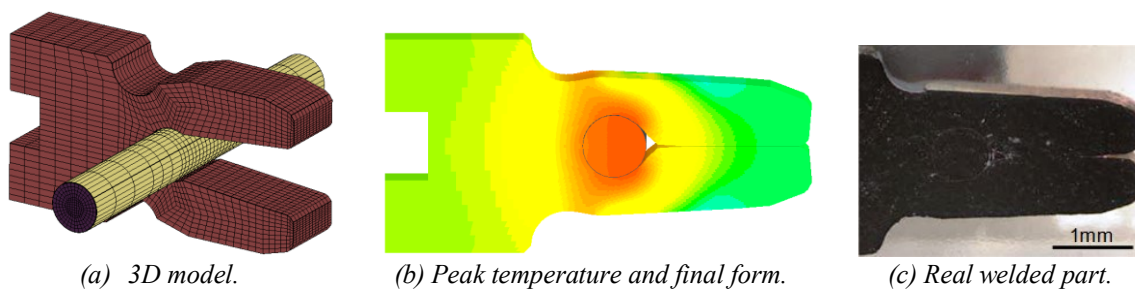

(a) 3D model. *(b) Peak temperature and final form.* *(c) Real welded part.*

Fig. 5: Hot staking (fusing) for joining wire to connector simulated with SORPAS 3D.

2.2 Design of rivet and die

In mechanical joining, the design of rivet is key to decide whether a joint can be made successfully. Similarly, the design of die is also critical to the quality of joining. In case of self-piercing riveting (SPR), if the rivet is too short or too long comparing to the total thickness of the sheets to be joined, or even with the correct size but the material of the rivet is not strong enough to penetrate into the sheets, the joint cannot be made properly. A lot of trial and error tests need to be done in order to find the suitable rivet for a given combination of sheets with

specific thickness and materials. For this purpose, numerical simulations are very useful to get the optimal design of rivets before doing any physical tests.

Fig. 6 shows an example of SPR with different designs of the rivet tip geometry. It shows that by a small change in the radius at the rivet tip, the resulted joint is with different interlock length, where the maximum setting force is also changing with different rivet designs.
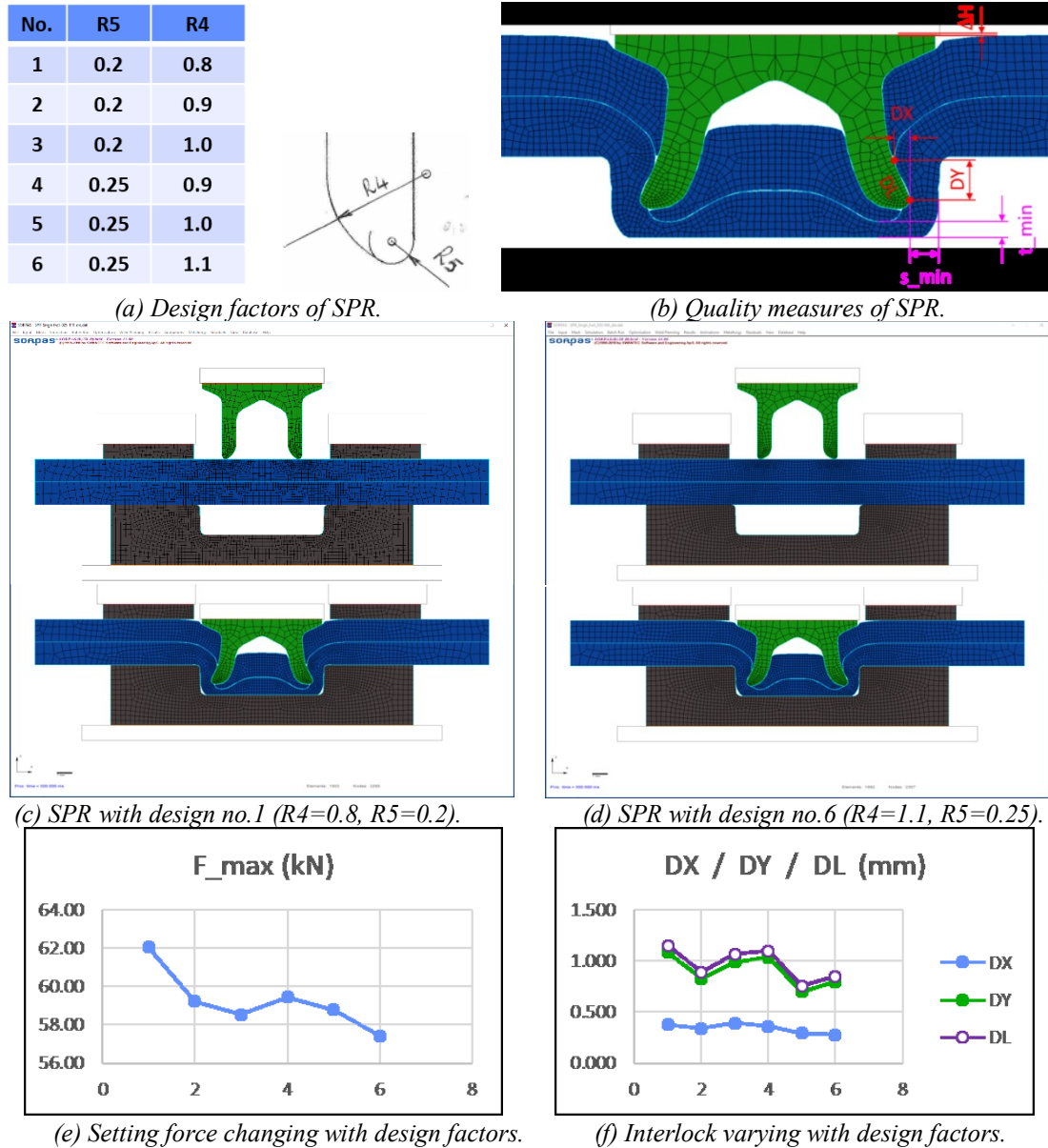
No.	R5	R4
1	0.2	0.8
2	0.2	0.9
3	0.2	1.0
4	0.25	0.9
5	0.25	1.0
6	0.25	1.1

(a) Design factors of SPR.

(b) Quality measures of SPR.

(c) SPR with design no.1 (R4=0.8, R5=0.2).

(d) SPR with design no.6 (R4=1.1, R5=0.25).

(e) Setting force changing with design factors.

(f) Interlock varying with design factors.

Fig. 6: Influence of design factors in self-piercing riveting (SPR) simulated with SORPAS 2D.

2.3 Design of electrodes

In spot welding, the shape and material of electrodes are important to produce different weld results. Fig. 7 shows an example of spot welding aluminum alloy. By changing the electrode tip face radius from 40mm to 150mm, the weld nugget size has reduced significantly with the same welding current, force and time.
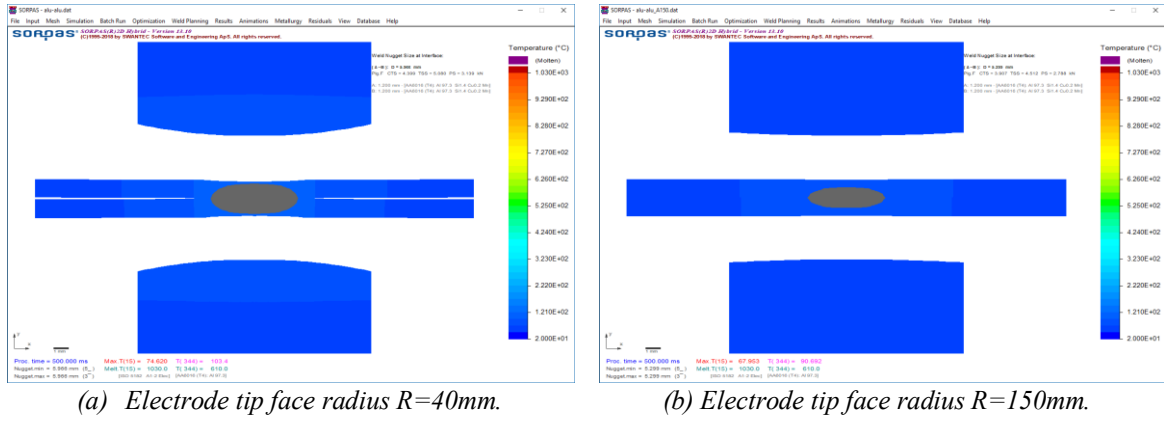
(a) Electrode tip face radius R=40mm.   *(b) Electrode tip face radius R=150mm.*

Fig. 7: Spot welding aluminum alloy with different design of electrodes simulated with SORPAS 2D.

2.4 Weld properties after welding

The material properties after welding is an important quality measure that is also a design factor related to the product structural design. It is possible to model the microstructures and hardness distribution after welding. Fig. 8 shows the predicted distribution of martensite, bainite, pearlite and ferrite, and also the hardness distribution with contributions of all phases.
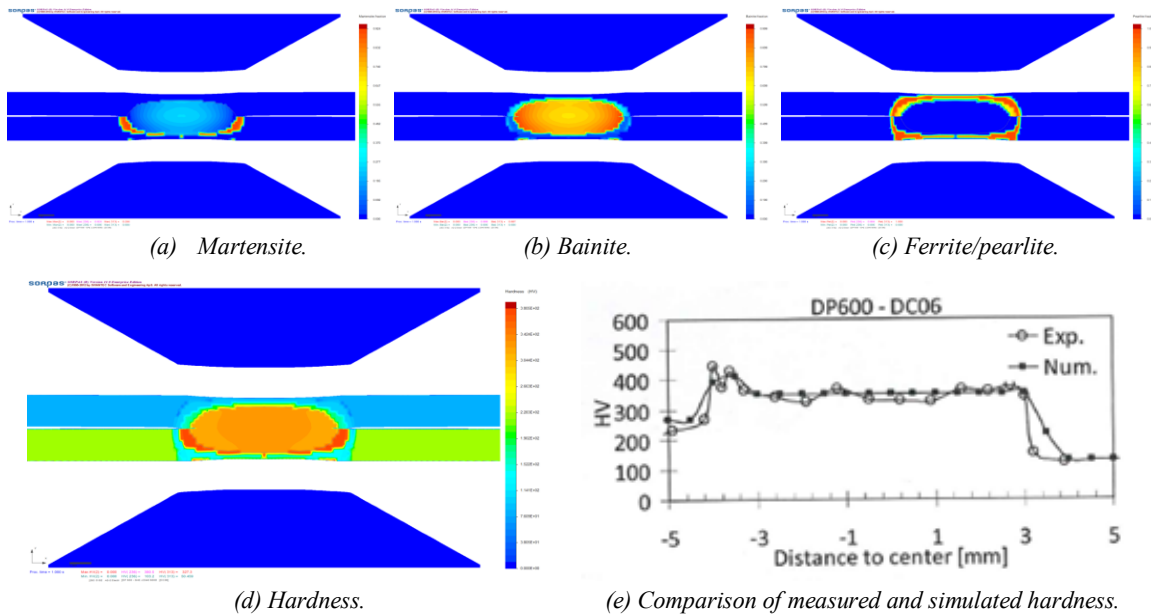

(a) Martensite.   *(b) Bainite.*   *(c) Ferrite/pearlite.*

(d) Hardness.   *(e) Comparison of measured and simulated hardness.*
Fig. 8: Microstructure and hardness distribution in spot welding of DC06-DP600.

2.5 Prediction of weld strengths

Evaluation of the weld strengths is essential for the car body design and for weld quality assurance. Already in the design phase when designing the welds and selecting materials to be welded, it would be good to know the possible weld strengths to be obtained from the welding production. This is possible to be simulated based on the optimized welding process parameters and then with the 3D simulation of the weld strength testing.

Fig. 9 shows one example of the complete simulation first with spot welding process simulation then followed with weld strength testing simulation with output of the load-elongation curve and the fracture mode.
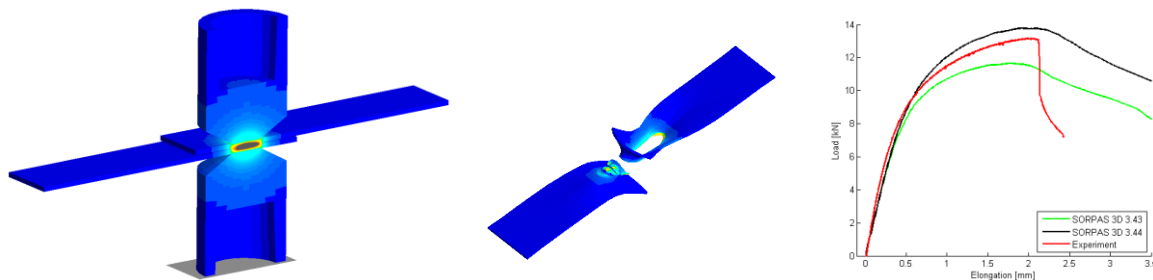

Fig. 9: Weld strength test simulation with SORPAS 3D.

3. Production-Oriented Simulation and Optimization

After many years developments and improvements especially with integration of the welding engineering expertise into the numerical simulations, the accuracy of the simulations has been substantially improved. This has provided the foundation for conducting more advanced simulations for the purpose of optimizations. With these new achievements, the simulation and optimization are getting directly to the welding production settings.

3.1 Prediction of splash (expulsion)

Splash or expulsion had been used as an indication of the welding process under action, but nowadays it is regarded as a defect due to environmental concerns and also for the quality of the welds. So, the splash (expulsion) limit is now used as the boundary conditions to find the welding process window.

In the welding labs, the splash limit is found by running a lot of experiments with welding tests or observations at production, see Fig 10. It is both costly and not friendly to the environment.
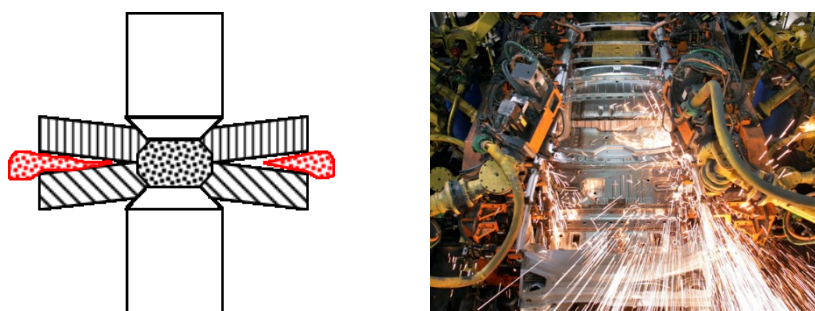

Fig. 10: Splash (expulsion) is considered as defect in welding production.

It is possible to predict the splash limit with SORPAS for spot welding of steels and aluminum alloys. Fig. 11 shows the predicted splash with the dynamic timing during the welding process and the level of the splash classified into low, medium and high.
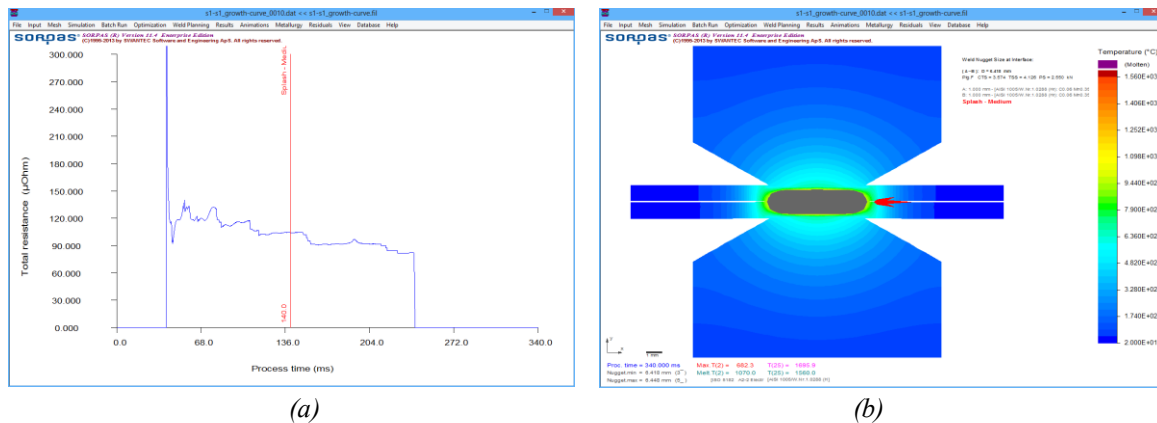
(a)   *(b)*

Fig. 11: Simulation with prediction of splash during welding. (a) Predicted starting time of splash in the welding process. (b) Resulted weld nugget sizes with indication of splash level.

3.2 Weldability and process window

There are two types of weldability tests proposed in the international standard ISO 14327:2004, including the weld growth curve and the weldability lobe.

The weld growth curve is made by running a series of weld tests with increasing weld current and then measuring the resulted weld nugget sizes until the splash limit. The weldability lobes are made by running more tests with a combination of two welding parameters with current-time or current-force.

Hundreds of tests need to be done to obtain these diagrams. In both diagrams, the process window can be found with a good range of current in the weld growth curve and the area of good parameter combinations in the weldability lobe.

With SORPAS® 2D, both diagrams can be generated automatically with predicted expulsion (splash) limits and the process window.

Fig. 12a shows an example of the simulated weld growth curve for spot welding of 1.0mm low carbon steel sheets with weld nugget diameters increasing as function of the weld current. The black points (square markers at the left side) mean no weld or undersized weld. The red points (triangle markers at the right side) indicate expulsions (or splashes). The green points (round markers) in the middle are good welds. The welding process window is indicated on the weld growth curve with the working range of weld current.

Fig. 12b shows an example of the simulated weldability lobes for spot welding of 1.0 mm low carbon steel sheets with varying weld current and time at a given weld force. The black points (square markers at the left side) are no weld or undersized welds. The red points (triangle markers at the right side) are oversized or expulsion (splash) welds. The green points (round markers) indicate the process window and range of good welds.
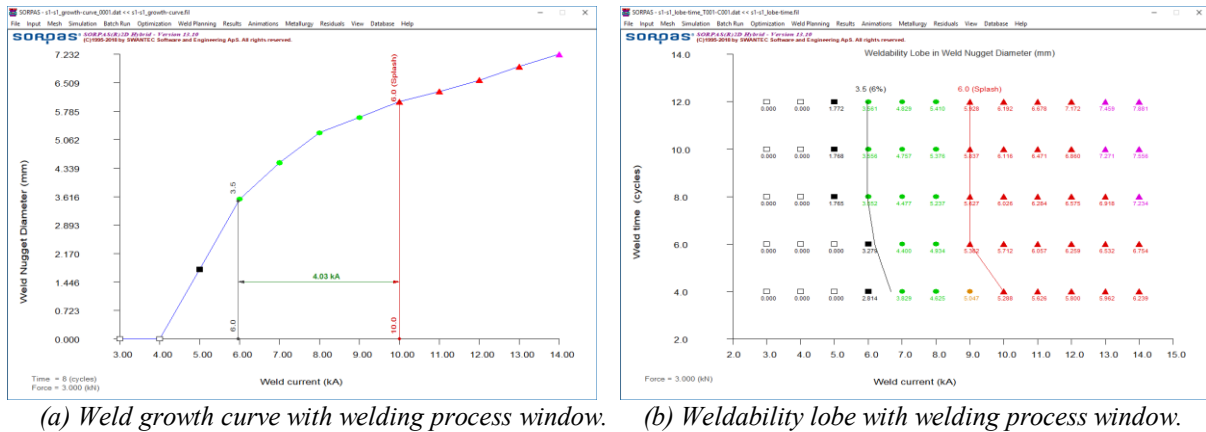
<table>
<tr><td>(a) Weld growth curve with welding process window.</td><td>(b) Weldability lobe with welding process window.</td></tr>
</table>

(a) Weld growth curve with welding process window.   *(b) Weldability lobe with welding process window.*

Fig. 12: Process window with weld growth curve and weldability lobe predicted with SORPAS 2D.

3.3 Process optimization and planning

One of the biggest challenges to welding engineers at production is to set up all welding process parameters for every weld in every welding machine. Even with usually recommendations of welding parameters form the weld planning department or other resources, a lot of weld tests still need to ne done to make sure every weld will be made a good weld.

The advanced function of Weld Planning in SORPAS has taken advantages of all optimization procedures to directly predict the optimal welding parameters with specific current, force and time for a specific weld task. The weld task is defined with combination of sheet thickness and materials and the choice of electrodes and welding machine.

Fig. 13 shows an example of the Weld Planning Report. It includes four parts:

a) the input information of the sheets, electrodes and type of welding machine;
b) the graphical display of the optimal welding process parameters;
c) the optimal weld current, force, weld time and hold time together with the predicted welding process window and splash limit;
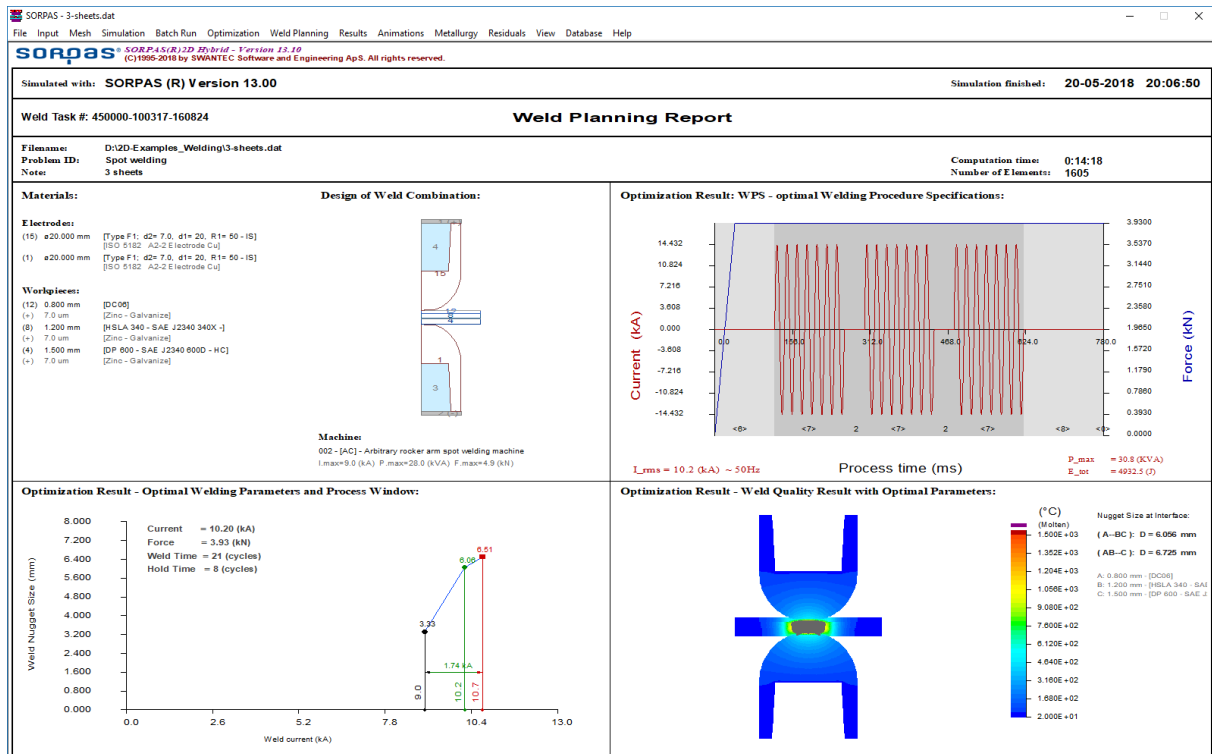d) the welding results obtained with the optimal welding process parameters.

Fig. 13: Weld planning with optimal welding parameters by SORPAS 2D.

3.4 Optimization with effect of electrode wear

Electrode wear is a general issue in resistance welding production. A lot of studies have been made to understand the cause of the electrode degradation, but it is very hard to predict the electrode life without physical tests. Fig. 14 shows the electrode tip diameter increasing with the number of welds, which is seen largely depending on the sheet materials and surface coating as well as process parameters.
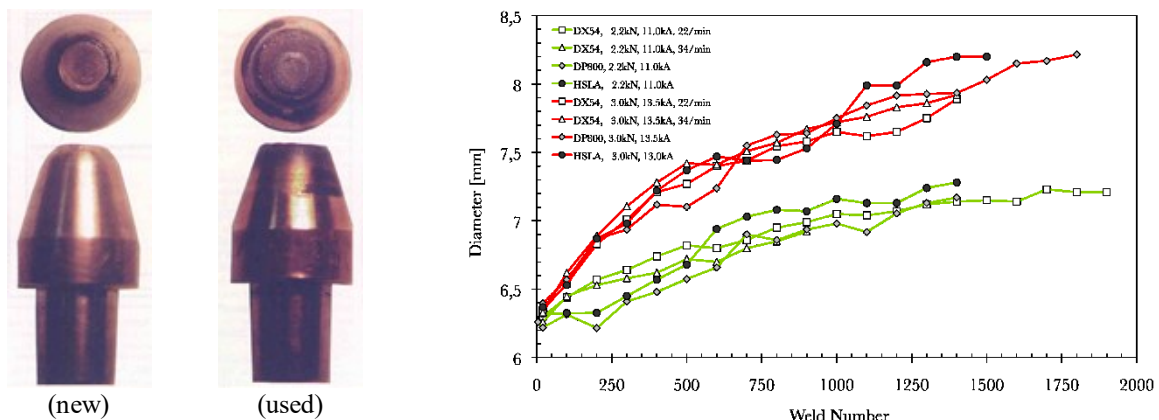

(new)   (used)

Fig. 14: Measured electrode wear as function of number of welds and welding parameters [6].

Many efforts have been made to model the degradation of electrode thereby to predict the electrode life. But, due to the complexity of process conditions in production, where the same electrodes may be used for different welding jobs, it is still quite difficult to predict the life of electrode by modeling.

However, an equally important demand is also to tell when the electrode is out of condition and shall be tip-dressed or replaced. For this purpose, the process optimization and planning functions can be applied to simulate with the used condition of electrodes and then trace the changes in the process window thereby decide necessary adjustment of the welding parameters.

Fig. 15 shows a comparison of two weldability lobes. One was made with new electrodes of Type F1 with tip diameter at 6mm and tip face radius at 40mm. The other one was made with used electrodes of tip diameter at 7mm and tip face radius at 150mm representing a worn and flattened electrode tip. Fig. 15a shows the weld nugget with new electrodes and with current 8kA, force 3kN and time 8 cycles. Fig. 15b shows the weld nugget with used electrodes and the same welding parameters. It is clear to see that the weld nugget got much smaller with the used electrodes. The process window has also moved towards larger current. To maintain the same weld qualities, the weld current may be increased to compensate the reduced weld nugget.
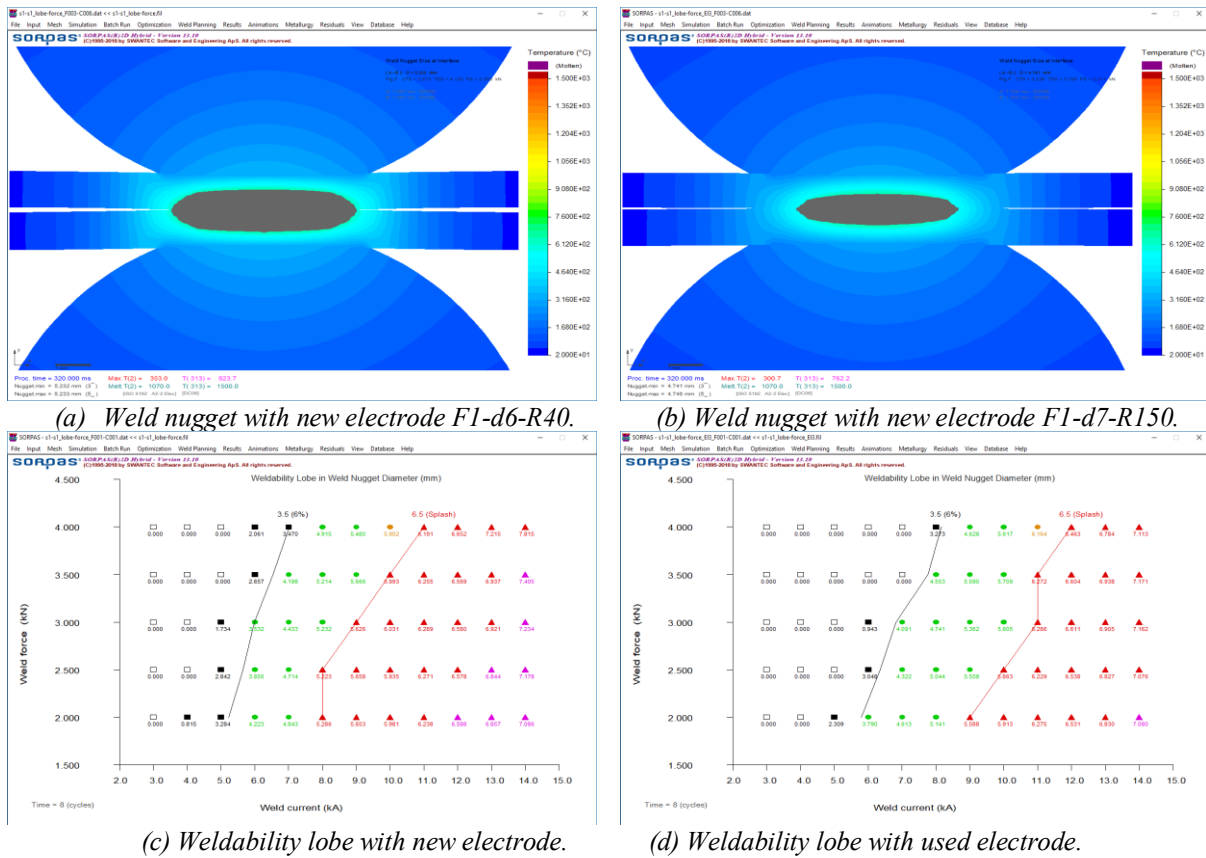

(a) Weld nugget with new electrode F1-d6-R40. (b) Weld nugget with new electrode F1-d7-R150.

(c) Weldability lobe with new electrode. (d) Weldability lobe with used electrode.

Fig. 15: Weldability lobe (process window) with new and used electrodes simulated with SORPAS 2D.

4. Control-Oriented Optimization with Machine Learning and Artificial Intelligence (AI)

The adaptive control systems have been increasingly applied in welding production to improve the stability of the welding production and consistency of the weld quality. As previously discussed, many welding problems can be solved by making optimal weld design and by making sufficient process optimizations. Both are important to provide the best conditions for running the welding production. The better work done in these 2 steps, the more stable production could be achieved. However, there are always unpredictable disturbances during the welding production due to process dynamics and irregularities of process conditions. The

adaptive control techniques are useful to deal with these unpredictable disturbances and process dynamics.
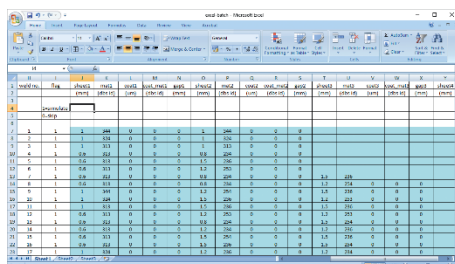
With the ultimate goal to achieve the best welding process and weld quality by support of numerical simulations and optimizations, further developments have been carried out to provide better optimized process parameters that can be directly transferred to the welding controllers.

New developments are also being discussed and prepared for closer interactions between the welding control with numerical optimizations. This will offer new potential to combine the advantages of numerical optimizations and adaptive control techniques through interactions of the numerical optimizations with databases, machine learning and artificial intelligence (AI).

4.1 Excel batch optimization and planning

To get into to the welding control, the first step is to generate optimized process parameters that can be transferred to the welding controller as the starting control parameters.
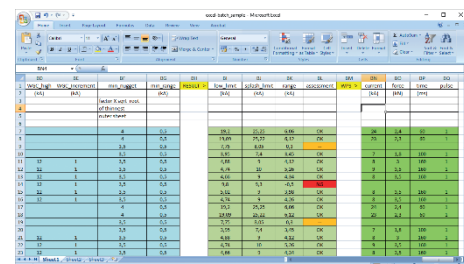
The Excel Batch Optimization and Planning function in SORPAS 2D is developed and now used by many customers to massively optimize and plan welding process parameters for spot welding of steels and aluminum alloys. With this new function, up to 500 welds with different sheet combinations can be simulated and optimized by directly reading input data from an Excel datasheet file and then automatically run batch optimizations. After finishing the Excel batch planning, the optimal welding parameters and process windows will be output back into the same Excel file with classifications to 3 weldability levels for "OK", "==", and "NG", see illustrations in Fig.16. This will massively speed up the weld process planning, which can also support production maintenance to improve production stability and weld quality.

Input data in Excel file.   *Output optimal parameters.*

Fig. 16: Excel batch optimization and planning to predict optimal welding parameters.

4.2 Adaptive simulation with dynamic welding control

The Excel Batch Planning function has made the numerical optimizations to provide support just before the welding control. The next step is to make interaction with the welding control by a new function which will be developed in the near future.

This new function will be the "adaptive simulation mode", that will allow dynamic feeding of welding process parameters into the simulation during the welding process. In this way, the simulation will work like a virtual welding machine. It will take the command from the control data and run simulation with the given process parameters and then feedback the welding results to the weld control. The weld control will then make necessary regulations and send new

command to the simulation, as illustrated in Fig. 17. This adaptive simulation mode can be used as virtual welding machine to support developments and improvements of the adaptive welding control algorithms.
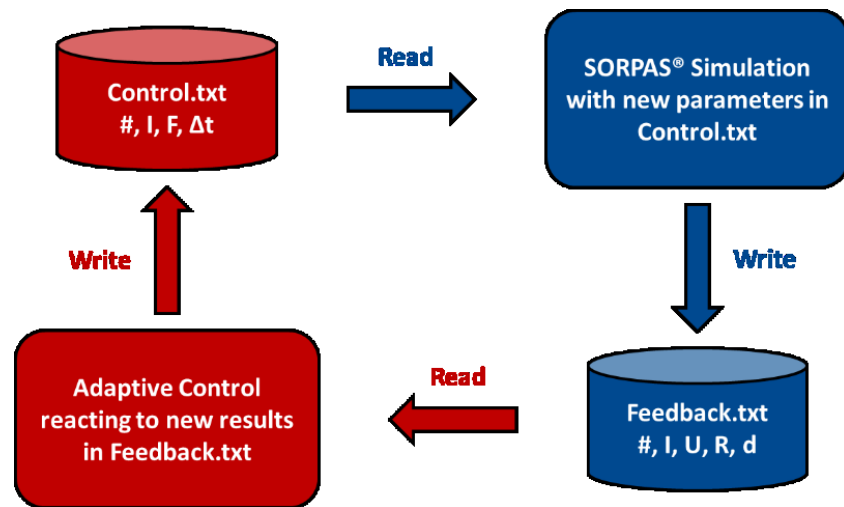

Fig. 17: The adaptive simulation mode to be implemented in SORPAS 2D.

4.3 Optimization with machine learning and artificial intelligence (AI)

One of the difficulties in numerical simulation and optimization is the lack of actual dynamic conditions during each individual welding process. The adaptive welding control system, on the other hand, can dynamically measure many process signals during each welding process, but it needs to have a good starting condition for each individual welding job to improve the reliability and stability of the welding process control.

Combining the advantages of both techniques will further improve the accuracy of numerical simulations and optimizations for each individual welding process, and will also speed up the running-in settings for the adaptive control system and foresee larger regulations needed for example related to electrode conditions etc. These communications would be possible with some new algorithms by machine learning and artificial intelligence (AI) to automatically make improvements of the simulations and optimizations.

Fig. 18 shows an outline of the communications between the systems in a welding production cell. Due to the fact that many companies already have their own databases with useful welding data, it is also possible to make such database as a reference when making decisions of the best welding conditions for a specific welding job.

Many new developments will be conducted in the next years to further explore the potential of numerical simulations and optimizations.
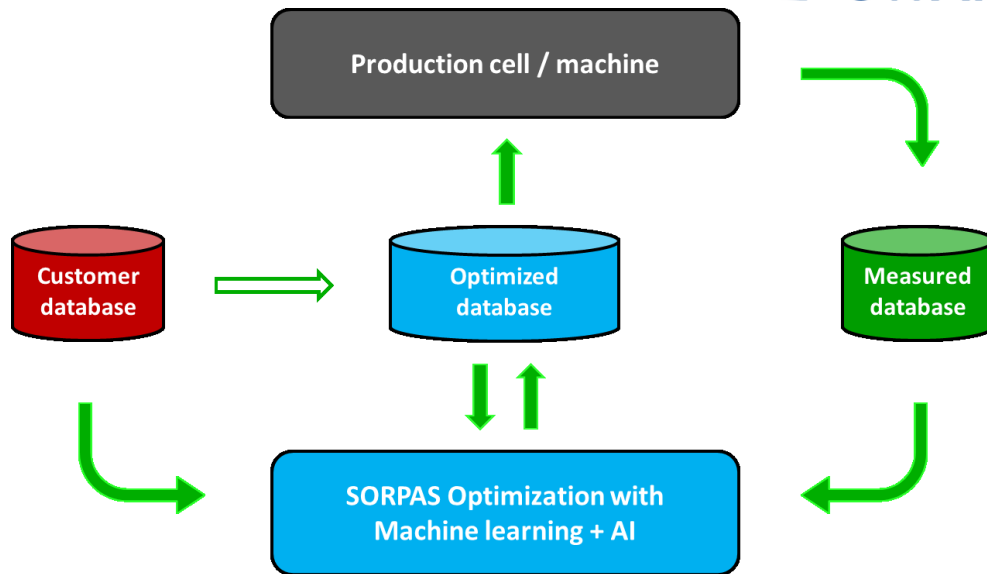
Fig. 18: Algorithm for optimization with machine learning and artificial intelligence (AI) to be implemented with SORPAS 2D.

5. Conclusions

Numerical simulations and optimizations have been applied in industry for solving various welding problems mainly categorized into three types, namely the deign related problems, production related problems and control related problem.

The potential to interact with machine learning and artificial intelligence (AI) will lead the new developments of numerical simulations and optimizations further towards control related applications and to get closer and even into the welding production controls.

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