Case study

Numerical Simulation of Welding Distortions (GMAW) in agricultural implements

By Guilherme Zanette - Manufacturing Engineer Stara Indústria de Implementos Agrícolas

The distortion caused by the welding process is a significant concern in the manufacturing of agricultural implements. Its effects often cause the assembly to be welded to fall outside the design tolerances. This manufacturing process frequently involves trial and error, rework, high try-out times, high costs, and dependence on experienced professionals. Ways to mitigate welding distortions are commonly used to ensure the dimensional integrity of welded assemblies. Based on the finite element method, CAE (Computer Aided Engineering) technology plays a vital role in predicting the distortions of the assembly, in a virtual environment, throughout the welding process. The distortion induced by arc welding (GMAW) in chassis main rails of agricultural implements was modeled and simulated in Simufact Welding. With this computational resource, it is possible to understand the model's behavior during the process, being a great resource in the decision-making of the welding analyst.

The validation results indicate that the numerical simulation of the welding process is fundamental for understanding the effects generated by the welding process, in the design of the fixture, and in the selection of the pre-deformation to enable the manufacturing of the assemblies within design tolerances.

Gas Metal Arc Welding (GMAW) is a welding process in which an electric arc forms between an electrode and the part. This arc heats the workpiece to its melting point, causing them to melt and create a joint. In GMAW welding, the thermomechanical behavior of materials is an essential factor in determining weld quality. Therefore, it should be carefully considered to avoid thermal distortion and residual stresses that affect the dimensional and structural integrity of the component. The process involves phase transformation, in which there are microstructure changes, and therefore the mechanical properties of the materials can differ significantly from those at room temperature. Thermal distortions depend heavily on boundary conditions, welding sequence, and parameters such as energy input. Understanding the thermomechanical behavior of materials and predicting distortion under different welding conditions is important to improve the manufacturing process.

The design of a welding process relies heavily on operator experience and a time-consuming trial-and-error approach that is inefficient and costly. As a solution, finite element analysis (FEM) focused on the welding process has become a viable option for understanding welded parts thermomechanical behavior and predicting the thermal distortion that can occur during welding. In addition, through welding simulations, welding process design ideas are generated for actual manufacturing under various conditions.

Welding simulation is a challenging problem since the thermomechanical behavior of welded parts is a multiphase problem by nature and is highly nonlinear, involving phase transformation and plastic deformation of welded components.

The analyst responsible for using the technology must know the theory involved in the simulation. Among the necessary knowledge needed, the complete understanding of the type of finite element to be used, formulation of the element, size of the element, the quality of the element, and how the simulation works are fundamental to obtaining results consistent with reality and making the most of the benefits that the technology offers.

Development

A self-propelled agricultural implement's chassis structure is formed by lateral main rails joined by cross members (Figure 1). The welding process makes this union. The chassis is a structural component that absorbs the greatest amount of energy during the impacts of agricultural operations.

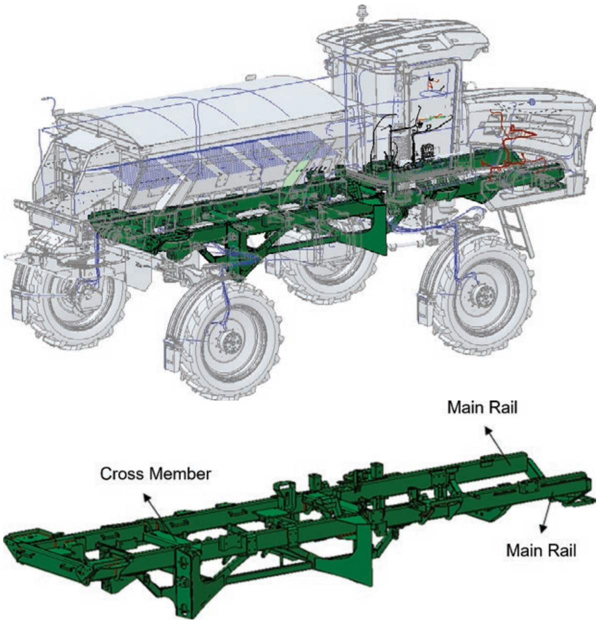

Figure 1 – Chassis of a self-propelled agricultural implement.

Due to the heavy welding load, companies choose to weld the chassis all "locked", with all the cross members bridged to minimize the effects of distortions.

Welding the main rail as a single set can be an excellent strategy to increase productivity and reduce cycle times. However, the big challenge lies in predicting the effects of welding distortions and finding a solution to meet design tolerances.

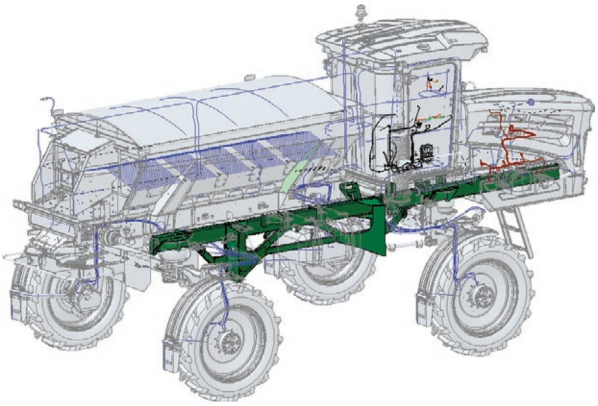

Figure 2 shows in detail the main rail, the object of this study, mounted on the implement.

Numerical model

The numerical model (Figure 3) of the main rail structure used in this study is comprised of hexahedral solid elements (HEX8, in Simufact Welding). MSC APEX software was used to prepare the finite element model to assign different sizes of meshes in the regions of greater thermal input (regions of interest) with 4 mm and in the other regions with 10 mm. The model was discretized with 389,721 nodes and 244,557 elements.

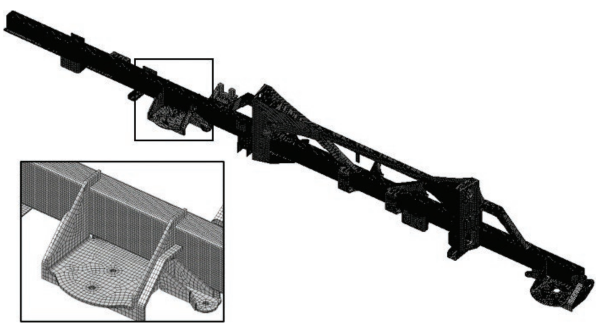

Figure 3 – Numerical Model – Finite Element (Solid).

The material used in the chassis main rail is structural steel and has the following properties:

- Elastic Modulus: $E_L = 210 \times 10^9$ Pa
- Poisson's Ratio: $\upsilon = 0,3$
- Density: $\gamma = 7850$ kg/m³
- Yield Stress: $\sigma_{esc} = 700 \times 10^6$ Pa
- Tangent Modulus: $E_{Tan} = 431 \times 10^6$ Pa

The additional material used is ER70-S6 and has the following properties:

- Wire diameter: 1.2 mm
- Elongation: 26 %
- Yield Stress: $\sigma_{esc} = 424 \times 10^6$ Pa
- Tensile Strength = 518×10^6 Pa

Mitigation of distortions in the welding process

The joining of components by the welding process generates numerous undesirable effects. Among them, the most critical are the distortions.

The distortions occur due to the high thermal input generated for the union of the materials (melting temperatures of the material), generating high tensions, causing the region to enter the plastic limit, causing "warping."

Knowing ways to minimize these distortions is essential to make proactive decisions and ensure the set manufactured by this manufacturing process. Figure 4 demonstrates different actions to mitigate welding distortions.

Figure 4 – Ways to mitigate welding distortions.

Among the actions to minimize distortions, we have:

- **Compensation:** consists of making a welding device with process dimensions, that is, creating a "wrong" fixture so that at the end of the process, the component is within the tolerances.
- **Pre-Deformation:** consists of tensioning the whole assembly through a force in the opposite direction of the deformation tendency.
- **Sequencing – Welding Direction:** change sequencing and welding directions, influencing the magnitude of distortions.
- **Parameters:** change parameters – voltage, current, welding speed, influence on the energy transferred and consequently on the distortions.
- **Gravity:** heavy assemblies in a correct welding position can mitigate distortions.
- **Weld critical items at the end of the process:** so, the component does not deform along with the other items.
- **Weld larger beads first:** thus, these beads will be cooled inside the welding device.
- **Geometry:** distortions can be generated due to stress concentrators referring to the component's geometry.
- **Boundary Conditions:** Position, quantity, forces of clamps, tables, wedges, pins, and stops, have a significant influence on distortions.
- **Cooling:** Cooling times, inside or outside the device, will influence distortions.

For each assembly to be welded, it is necessary to analyze and find a viable solution to guarantee the tolerances requested.

Numerical simulation of welding distortions

With the finite element model prepared, with some simplifications, knowing the type and formulation of the finite element used, defining the size and quantity of the elements, and checking their quality, the mesh was imported into Simufact Welding software.

The parameters used are 295 Amperes and 25 Volts for thick plates and 260 Amperes and 23 Volts for thin plates. The welding speed varies between 35 to 70 cm/min. Figure 5A shows the welds used in the model, and Figure 5B shows the sequencing and welding directions used.

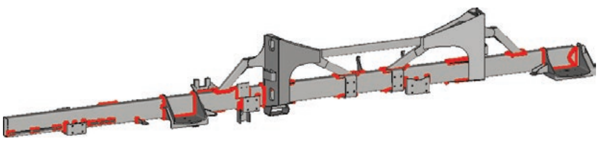

Figure 5A – Welds used in the model (22 mts).

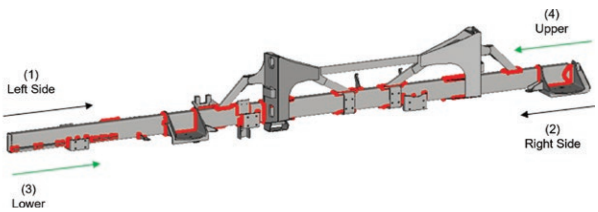

Figure 5B – Sequencing and welding directions in the model.

With well-defined input data, parameters, constraints, materials, input temperatures, and weld trajectories, Simufact Welding will calculate for each node of the numerical model results of temperatures, stresses, distortions, and forces in the components throughout the cycle. Its interpretation will generate subsidies to understand the behavior of the assembly and find an optimized way to ensure its dimensions.

A calculation methodology was defined to get the most out of this technology. The search for the solution will go through the following topics:

- **Analysis of the deformation trend:** analysis with the model with few restrictions, on top of stands, to understand the influence only of the welding process on the set.
- **Creation of new boundary conditions:** with the results of the trend analysis, a new model is created with some way to mitigate the distortions shown in section 2.3.
- **Re-analysis to minimize distortions:** new analysis with new boundary conditions to numerically verify if the proposed solution was successful.

Analysis of the deformation trend

In the strain trend analysis, the model is as free as possible, supported on a table, and with upper clamps so that the set does not tip over. Figure 6 shows the analyzed model.

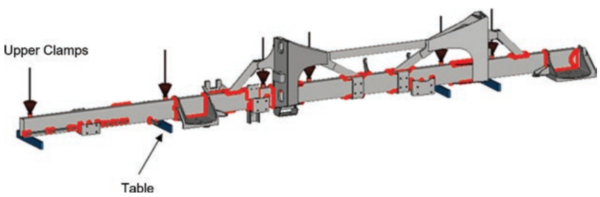

Figure 6 – Model for trend analysis.

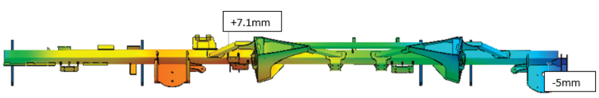

Figure 7 – Displacements in "y" – Trend.

Figure 8 – Direction of displacements – Trend (initial geometry transparent).

With the model at room temperature (20 °C) and without the upper clamps, we verified the distortions in the "y" axis, transverse direction to the main rail, where are the largest displacements.

Figure 7 shows the largest "y" displacements of the model. Displacement values of negative 5mm are observed at the right end of the main rail and positive 7mm in the central region of the main rail.

Figure 8 shows, on a exaggerated scale, the direction of the deformations for a better visualization of the effects generated by the process. Figure 9 shows the reference axes of the numerical model.

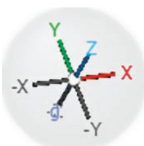

Figure 9 – Model reference axes.

Creation of new boundary conditions

With the results of distortions of the trend analysis, it was decided to use pre-deformation in the model. With the model tacked in the design position, the regions of greatest deformation are moved in the opposite direction through a force — the model is deformed with the aid of rotating pins. In the right side, 5 mm positive was used, and in the central region, 7 mm negative (reference axes of Figure 9 are used).

The model is pre-deformed within the elastic regime. Figure 10 shows the new numerical model with pre-deformation. Figure 11 shows the deformed model at the beginning of the process.

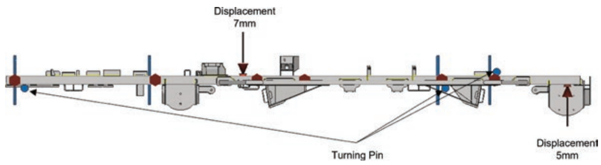

Figure 10 – Numerical model with pre-deformation.

Figure 11 – Deformed model at the beginning of the process.

Re-analysis in order to minimise distortions

The pre-deformed model was reanalyzed using the same parameters and weld sequencing. Figure 12 shows the displacements of the model at the beginning of the process, with the dotted main rail.

With the model cooled and removing the pre-deformation forces, the results of the new distortions were interpreted. Figure 13 shows the distortions at the end of the process of the preformed model.

In the right extremity, maximum displacements of + 1 mm were obtained, with a reduction of 80 % in the distortions in that region. In the central area, a maximum displacement of - 0.88 mm was obtained, a reduction of 87.4 % in the distortions in that region.

Numerically, the way to minimize welding distortions through pre-deformation was successful.

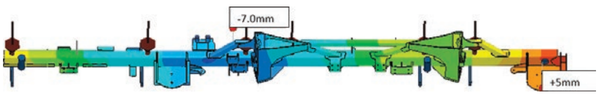

Figure 12 – Displacements at the beginning of the process — model with pre-deformation.

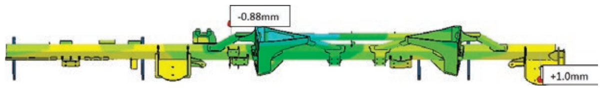

Figure 13 – Displacements at the end of the process — model with pre-deformation.

Welding fixture design

The results obtained in the Simufact Welding were essential for the design of the welding fixture. The conception of the device was based precisely on the models analyzed here.

The force required for the pre-deformation displacements was found in the simulation, facilitating and optimizing the selection of the hydropneumatic cylinders.

Figure 14 shows the model analyzed with the solution to minimize distortions and ensure its dimension, and Figure 15 shows the design of the welding device. Figure 16 shows the robotic cell for welding the chassis main rails of agricultural implements.

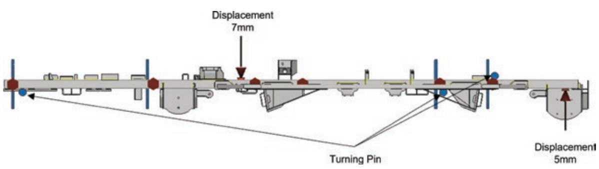

Figure 14 – Model for the manufacture of the welding device.

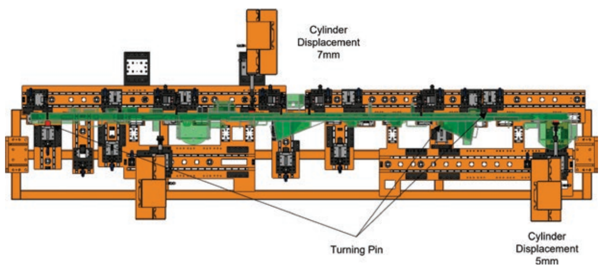

Figure 15 – Welding Device.

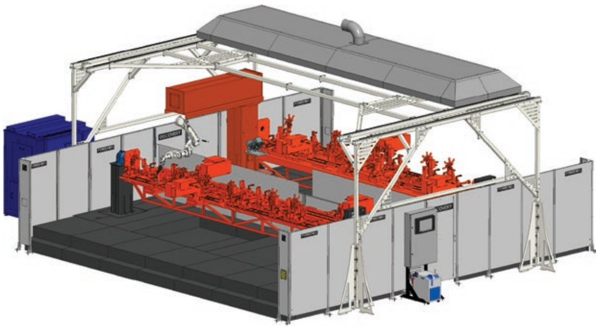

Figure 16 – Robotic cell for welding the main rails.

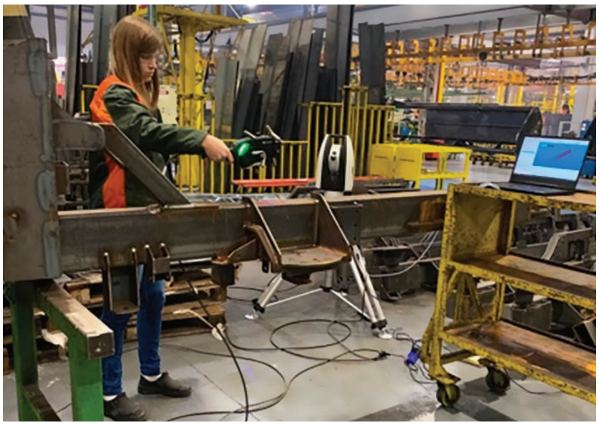

Figure 17 - Scanning of post-welding main rail displacements with Hexagon-Leica Laser Tracker.

Simufact Welding was fundamental for the success of the project. With the help of the technology, the entire behavior of the main rail was predicted before being welded, reducing try-out times, and optimizing device restrictions, cooling times, and cylinder forces.

The main rail was welded and then scanned with the Hexagon-Leica Laser Tracker model AT-960MR equipment with absolute AS1 scanner, T-Probe, and the help of the PC-DMIS software to verify the displacement deviations caused by the "Digital Twin" process.

Figure 17 demonstrates the measurement/scanning of the deviations (in mm) for the creation of the "digital twin" between the simulation and the main rail welded in practice for later evaluation.

Figure 18 shows the deviations (in mm) for the welded main rail in practice, staying within the tolerances requested by product engineering.

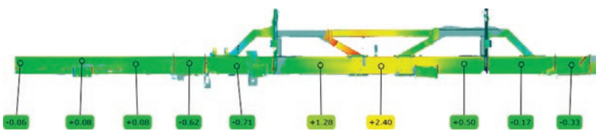

Figure 18 – Deviations of displacements of the main rail — Best Fit.

About Stara Agricultural Implements industry

Stara Indústria de Implementos Agrícolas is located in the city of Não-Me-Toque – Rio Grande do Sul – Brazil. The company's mission is to be a pioneer in intelligent solutions for agribusiness. Among the manufacturing processes, the Methods and Processes (Welding) sector is constantly evolving, seeking more and more technologies that facilitate, reduce costs, and increase the quality of our products and services.

Hexagon is a global leader in digital reality solutions, combining sensor, software and autonomous technologies. We are putting data to work to boost efficiency, productivity, quality and safety across industrial, manufacturing, infrastructure, public sector, and mobility applications.

Our technologies are shaping production and people-related ecosystems to become increasingly connected and autonomous – ensuring a scalable, sustainable future.

Hexagon's Manufacturing Intelligence division provides solutions that use data from design and engineering, production and metrology to make manufacturing smarter.

Learn more about Hexagon (Nasdaq Stockholm: HEXA B) at hexagon.com and follow us @HexagonAB.