REAL-TIME WELDING SIMULATION FOR EDUCATION

O. MOKROV*, M. SIMON*, A. SCHMIDT*, U. REISGEN*,
A. BEHMEL**, J. MARTIN**, A. BECIROVIC*** and
D. RUDOLPH****

**Institut für Schweißtechnik und Fügetechnik der RWTH Aachen University, 52062 Aachen, Germany*
***Institute of Design & Communication der FH JOANNEUM Gesellschaft mbH, 8020 Graz, Austria*
****Fronius International GmbH, 4600 Wels-Thalheim, Austria*
*****AUDI AG, Neckarsulm, Germany*

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ABSTRACT

Virtual reality training systems are state-of-the-art technology in welding education and are mainly meant to teach the manual skills needed for proper welding. In combination with computational numerical welding process simulation such systems can also be used to investigate the influence of different welding parameters on close-to-reality welding results. In this work, a virtual welding training system has been combined with physical welding process simulation algorithms that are optimised for near-real-time calculations and thereby enable a trainee to visualise and learn the influence of different welding parameters in a fast and cost-efficient way.

Keywords: Arc Welding, Visualization, Weld Pool, Education, Modelling

INTRODUCTION AND MOTIVIATION

Virtual Reality Training Systems are well known and well established in many different disciplines. One example are Flight Simulation Training Systems. In welding education, such systems are state-of-the-art when it comes to learn the manual skills needed for proper welding. In combination with computational numerical welding process simulation, it is possible to enhance such Virtual Reality Training Systems and therefore to enable a trainee to visualize and learn the influence of different welding parameters in a fast and cost-efficient way. To our knowledge, there is no virtual welding training system available currently that combines the advantages of virtual environments and physically calculated welding results into one system.

The use of computational simulation methods based on physical models for the investigation of arc welding processes is an established engineering method [1,2]. It is an efficient way to find necessary welding parameters, especially for tasks that exceed usual or well-known requirements. However, numerical welding process simulation has a trade-off between calculation time and result accuracy. The calculation of half a second of welding with high physical accuracy can easily take several weeks, even on a high-performance computing system [3].

To overcome these restraints regarding the usage of numerical welding simulation algorithms within Virtual Reality Training Systems, a research project has been executed that focused on the solution of the following challenges:

- Based on the welding simulation algorithms programmed for the SimWeld® platform [4] the simulation models have to be enhanced to allow transient calculation for the process simulation of manual GMA welding.
- For real-time simulations and visualizations in a virtual reality framework a framerate of at least 25 Hz is mandatory. An extensive acceleration of the transient numerical welding simulation algorithms is necessary to allow the computation in or near real-time.
- Based on the virtual welding training system Fronius Virtual Welding® a visualization module for the simulation results has to be designed and implemented.
- These two software systems have to be coupled to interact in a way that minimizes delays.

This article summarizes the results of the research project.

INITIAL STEADY STATE MODEL OF GMA WELDING IN SIMWELD®

Since 2001 the simulation group of the Welding and Joining Institute of RWTH Aachen University (ISF) has been carrying out research on arc welding processes to formulate physical models that, after being implemented into software (SimWeld® – Welding Process Simulation Software [5-7]), allow to calculate weld seam geometry and heat input and distribution within a few minutes on a standard personal computer. This kind of simulation is referred to as welding process simulation [8], which covers a macroscopic area of the construction component (welding and heat affected zone without material transformations) with a considered time interval between a few milliseconds and a few seconds.

The model architecture of the steady-state simulation algorithms implemented in SimWeld® is shown in Fig. 1: based on the given welding parameters, material properties and power source control algorithms, in the first part of the simulation, the Wire Drop Arc Model is calculating an average heat and mass input as well as an arc pressure distribution for a defined welding time. This result then serves as an input parameter for the Weld Pool and Seam Formation model and the Heat Flow model: The former one calculates the weld pool and seam geometry while the latter one calculates the heat flow within the complete macroscopic area of the work-piece.

With this model implementation the calculation of one simulation iteration that covers all three models takes about 5 minutes on a common office PC, which is much less time compared to other welding process simulation algorithms [3]. This is solely possible, because fluid flows as well as magneto-hydrodynamic effects in the weld pool and arc area are not included in the calculation directly but in the form of simplified compensation algorithms.

However, even this rather quick calculation is by far not fast enough to be applied in a virtual reality welding training system, where the trainee has to get a prompt response to his actions in order to benefit from this system. At the same time, the model architecture has to be modified in a way that it allows transient calculations to provide results for manual welding, where the welding velocity, the torch angles and the torch distance are irregular in comparison to robotic welding and even small corrections of the trainee by moving the torch backwards have to be considered. Therefore, the initial steady-state version of SimWeld® was used only as a starting point for the development of a fast transient calculation with the aim of eventually achieving real-time performance.

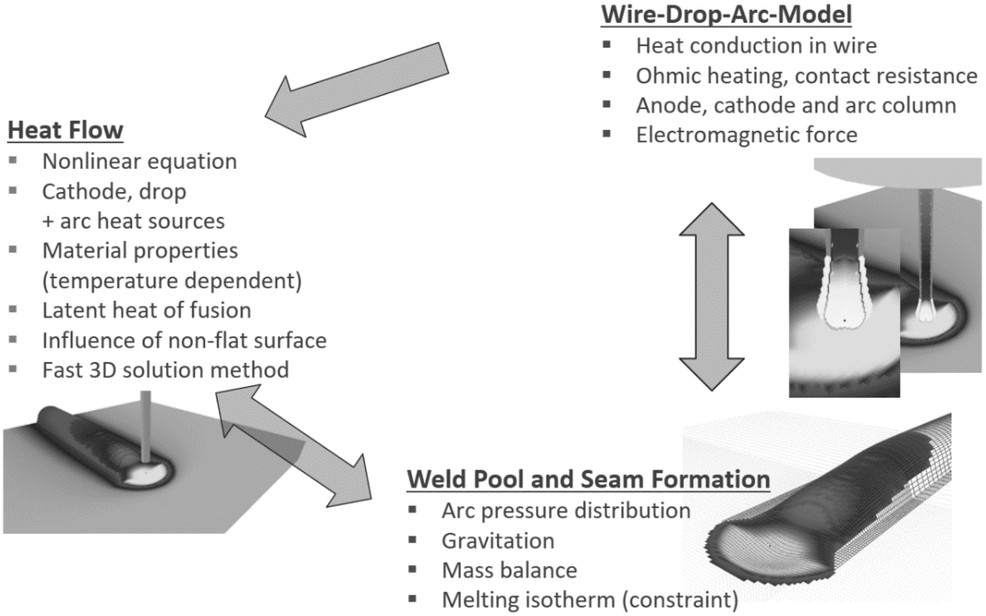

Fig. 1 Physical models implemented in SimWeld® and their interactions

A TRANSIENT SIMULATION MODEL OF GMA WELDING FOR REAL-TIME PROCESS SIMULATION

The transient model architecture that was developed is based on the steady-state algorithms of SimWeld® but allows the transient execution of the GMA welding process simulation. The base Wire Drop Arc Model in Fig. 1 is already transient and able to simulate the heat- and droplet mass transfers to the weld pool. Nevertheless, it was necessary to add the reaction of the electrical circuit on the variable stick-out to the model. In the main simulation loop, each iteration covers a time of 0.04 s. The first step in each iteration is the execution of the Wire Drop Arc Model that includes an inner loop where each iteration covers 0.1 ms. This model is able to react on current pulses and short circuits. For a simulated time of 0.04 s it generates the following average results: voltage, heat input of the arc cathode energy as well as heat, mass and velocity of the droplet.

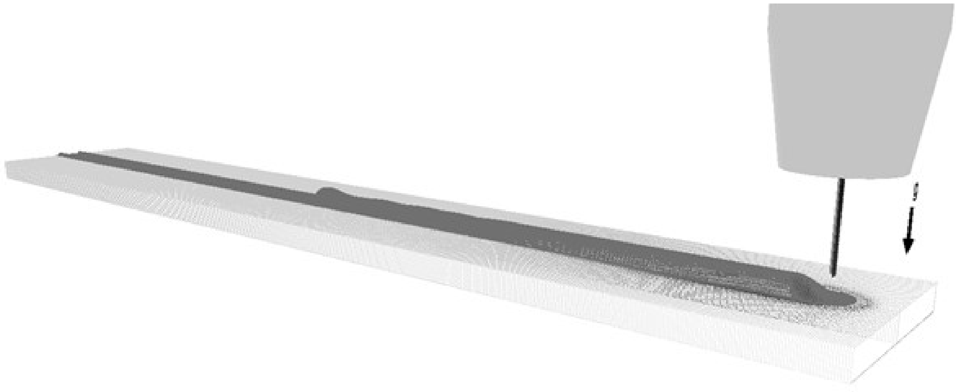

Fig. 2 Example of the result of a transient Simulation in SimWeld®

These average results are used as input parameters for both other sub-models in the main loop iteration. First of all, the tentative top surface of the weld pool from the previous main loop iteration will be modified proportionally to the droplet mass. In a second step, the distributions of cathode heat input and droplets effect, which are functions of wire speed, current and voltage of the arc and melting front location, are calculated. Then, these distributions are modified according to the torch position and the torch angles in relation to the weld pool, to be used subsequently as input parameters in the heat transfer computation of the weld pool and HAZ. The last step in the main loop iteration is the calculation of the modifications of the weld pool surface that maintain a balance of pressures, taking into account: surface tension, mass balance in the weld pool, gravitation and pressure of the arc. An underlying assumption here is that the transient effects of the changes during the period of 0.04 s are negligible. The results of this simulation procedure are shown in Fig. 2, where it can also be seen that the initial and the end of the transient weld were retrieved in the simulation.

In parallel to the development of a transient simulation model of GMA welding the model structure was modified to allow a significant speedup in calculation time with the aim to reach a frequency of 25 simulation iterations per second. As a first step to this goal, a prototype has been developed, which allowed the determination of the calculation time for one simulation iteration and the fraction of this time for each model in SimWeld®.

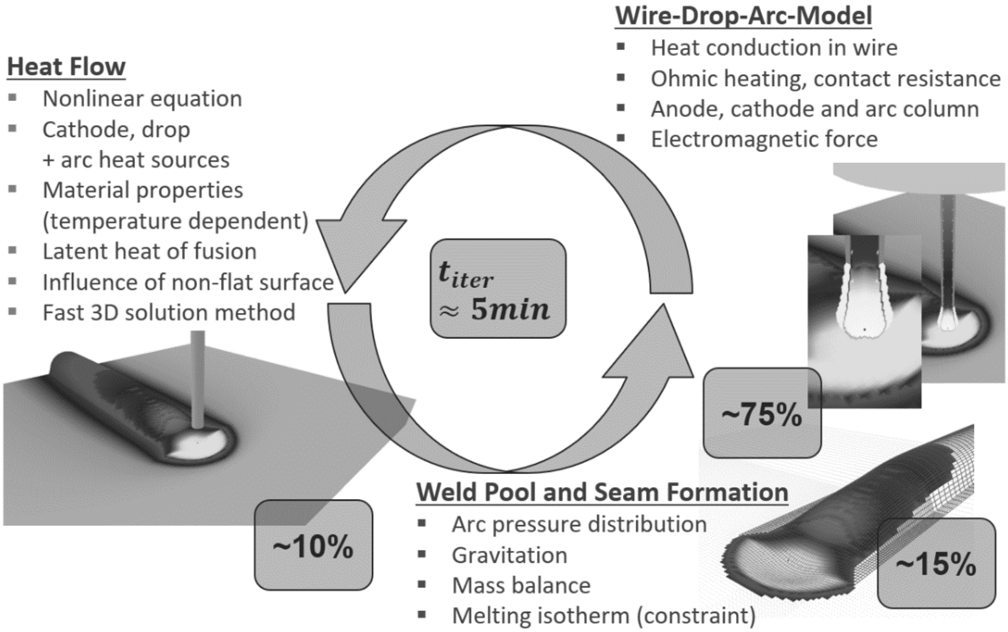

Fig. 3 Calculation time for one steady-state iteration of all physical models as well as the according fraction of calculation time for each model before the speed up and restructuring of the algorithms

The result based on simulations with a regular office PC is shown in Fig. 3: The overall calculation time for one iteration is about five minutes, where the Wire Drop Arc Model takes about 75 %, the Weld Pool and Seam Formation Model 15 % and the Heat Flow Model 10 % of the calculation time. Further investigations have shown that 80 % of the calculation time within the Wire Drop Arc Model were needed for the calculation of the heat transfer. The transient sub-models were reduced in dimensions from 2D to 1D:

- wire electrode heating
- electrode metal melting
- droplet formation
- droplets transfer to melting pool
- electric arc plasma area

The sub-model of Weld Pool and Seam Formation has been restricted in two iteration loops: first with fast convergence and coarse results and second with slow convergence and fine results. All non-linear effects are neglected during each time step and only taken into account between two succeeding time steps. Additionally, the calculation area of the Heat Flow sub-model has been limited to an area that covers the molten zone as closely as possible. Outside of this area, a different concept is used, see Fig. 6. The temperature dependent material properties are pre-calculated.

The result of restructuring the simulation models and accelerating the algorithms lead to a significantly reduced simulation time of less than 1 s per iteration (Fig. 4), which means an acceleration by factor of 300. This is a remarkable result although it does not fulfil the requirement of 40 ms per iteration for real-time simulations and visualizations in a virtual reality framework.

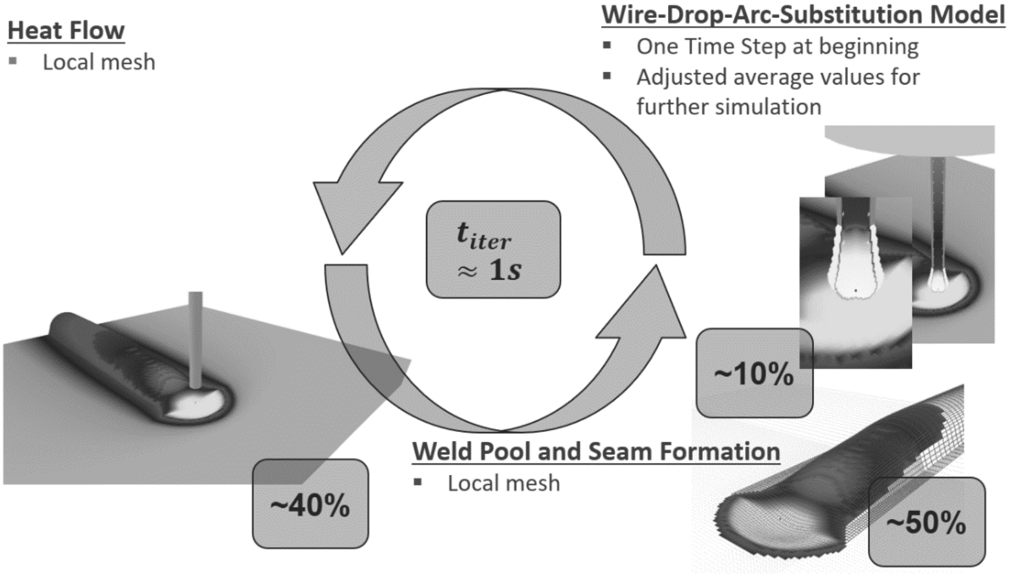

Fig. 4 Calculation time for one transient iteration of all physical models as well as the according fraction of calculation time for each model after the speed up and restructuring of the algorithms

IMPROVEMENTS OF THE HEAT INPUT DISTRIBUTION IN THE ARC CATHODE AREA

In the GMA welding process, an arc plasma burns between the work piece (cathode) and the melting wire electrode (anode). For the prediction of the weld seam geometry the calculation of the temperature fields is necessary. The conversion of electrical energy of the arc to heat energy to the materials of the cathode and the anode happens in thin layers of the arc adjacent to the material boundaries. In GMA process simulation, the distribution of the generated heat flux is usually described as a 2D Gaussian distribution that is applied to the weld pool (Fig. 5 - left).

Current results of fundamental research regarding the cathode area of GMA welding processes show that further improvements concerning the accuracy of the simulation results can be reached by a more detailed description of the physical processes in the cathode area. Although in this project, one main objective is the acceleration of the simulation algorithms, the new heat flux distribution in the cathode area can be assumed as a simplified consideration, to counteract the loss of accuracy caused by the simplifications that were made to reach the main objective.

In [9] it has been shown that a different heat input distribution appears (Fig. 5 - right) when taking into account effects of evaporation, as a reduction of the probability of an elementary cathode spot by evaporation is hypothesized. Therefore, the effects of evaporation not only on heat transfer but also on heat generation in the cathode region were taken into account. In order to achieve real-time calculation, this model cannot be used directly. An additional algorithm was developed to consider a distribution of the resulting heat flux, which resembles the physically in depth result. Therefore, a shape-matched distribution of the resulting heat flux will be used in the accelerated model. This represents a reasonable trade-off between calculation time and physical depth description.

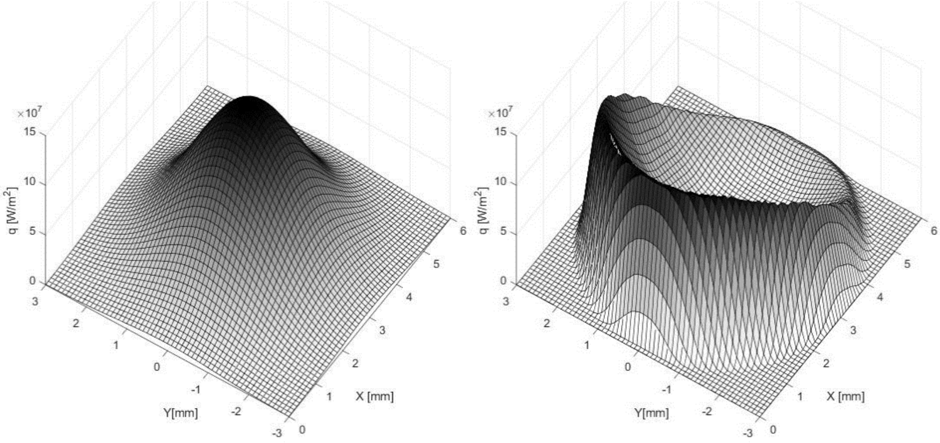

Fig. 5 Heat energy distribution in the cathode area: left – Gaussian distribution; right – distribution modified by evaporation

ALGORITHM FOR REAL-TIME GMA WELDING PROCESS SIMULATION

The described model modifications are the fundamental parts to reach the goal of a real-time welding process simulation software for educational purposes. This fundamental part can be used only with an algorithm that allows a fast and appropriate transient simulation for the usage in a Virtual Welding Training System.

Such an algorithm was developed based on the simulation algorithm of SimWeld®. Additionally a concept of dual local/global calculation is used: the heat transfer model consist of two simulation areas (Fig. 6). For each area a model of transient heat transfer was formulated. The first, local area is a free boundary condition area with the free surface of the weld pool. The second, global area includes the local area and is used for heat transfer calculation only.

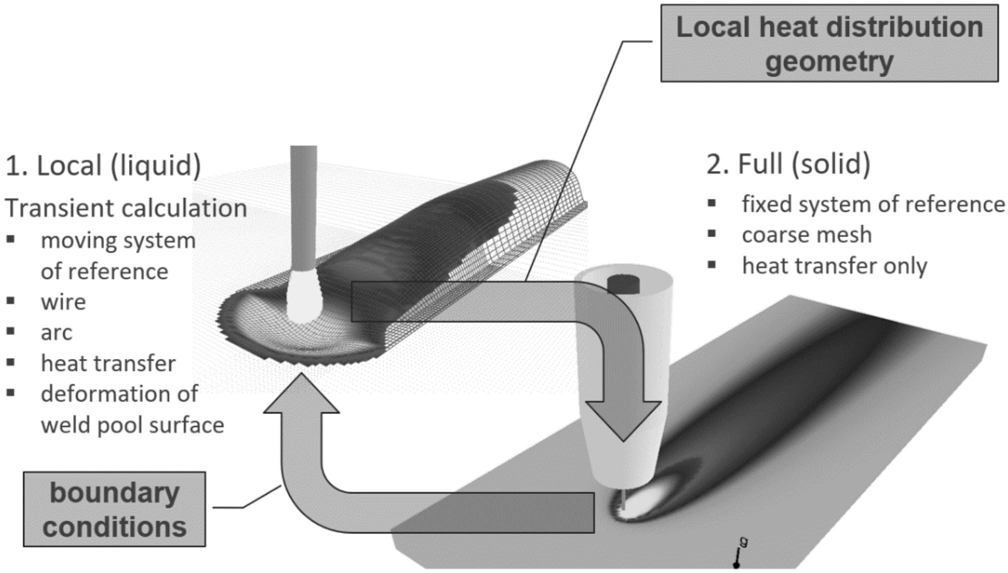

Fig. 6 Local/Global Calculation

Within the framework of this concept, the calculation is divided into two stages and accordingly into two calculation meshes. In the first step, the transient local calculation is performed in a moving reference frame according to the torch position. A fine mesh in this step allows to calculate the processes in the wire, in the arc, the heat transfer in the melt pool and HAZ as well as the formation of the melt pool surface with acceptable accuracy. The sub-model of the surface formation of the weld seam is adapted to the transient boundary condition and to the other sub-models. These modifications allow a simulation in transient mode with an erratically moving torch in the local mesh, which is usually the case in manual welding. In the second step, the heat input of the first step is used for calculation of the global heat transfer across the entire work piece in a fixed reference frame and a relatively coarse mesh.

COMPARISON OF SIMULATED AND EXPERIMENTAL RESULTS

The implemented simulation algorithms that are described above are designed to allow a fast calculation to be used in a virtual reality educational environment with the goal of allowing the trainee to benefit from physically based virtual welding results. For this purpose, in the trade-off-system of calculation time and result accuracy the balance was tilted in favour of a short calculation time over a high accuracy of the simulation result: the goal is that the general tendencies in the simulation were in sufficiently realistic accordance with the results of the actual weld. This approach is supported further by the argument that, when considering that many cross sections will be calculated in the transient simulation, the errors of each of the calculations will average out over a larger time interval.

To provide this goal, the simulation results have to be compared with experimental data. For this reason, welding experiments have been executed including transient measurement of current and voltage as well as cross-sections of the weld seam.

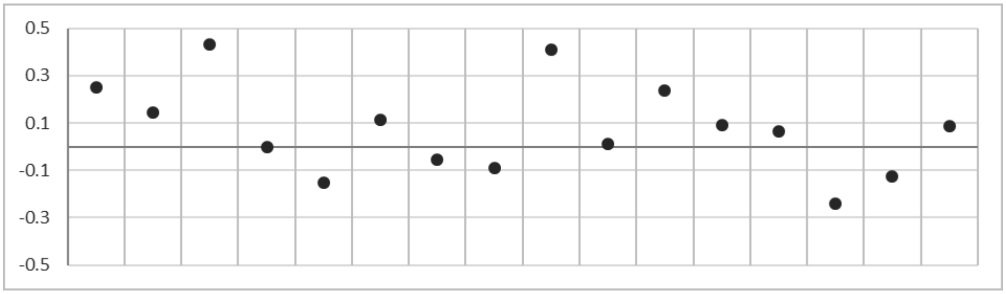

Fig. 7 Normalized deviation of experimental and simulated weld seam area (positive means overestimated seam area in simulation, negative means underestimated)

The comparison of the experimental and the simulated results shows that the normalized area deviation between experimental and simulated results is between -0.24 and +0.44 (Fig. 7) as well as that the deviation of the heat input is between -10 % and +10 % (Fig. 8)

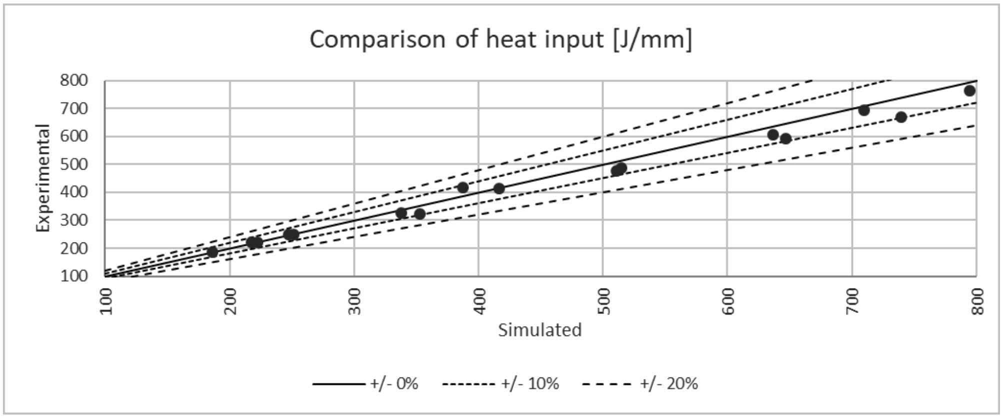

Fig. 8 Comparison of experimental and simulated heat input in J/mm, taking into account an efficiency factor of approx. 80 %

COMBINED VIRTUAL REALITY TRAINING SYSTEM AND PHYSICAL WELDING PROCESS SIMULATION

To connect the virtual reality training system and the numerical welding simulation models, an interface for the two systems has been defined. Therefore the approach of dynamic linked libraries was followed where the Fronius Virtual Welding® system uses a specially implemented SimWeld® DLL to provide the simulation results.

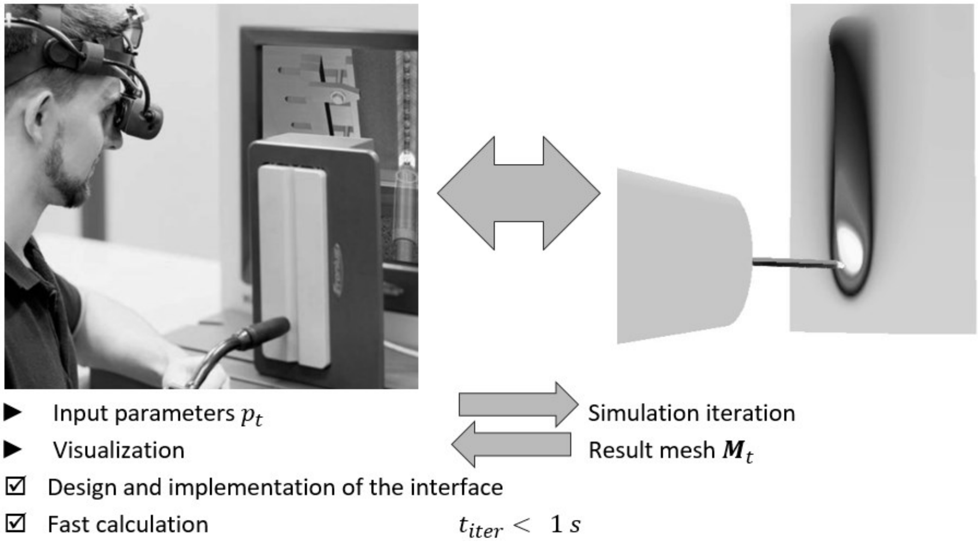

Fig. 9 Interaction of Fronius Virtual Welding® (left) and SimWeld® DLL (right)

Fig. 9 demonstrates the basic workflow: The user uses the virtual reality platform to define the basic welding parameters and to start the training. In the background these parameters are transferred to the simulation algorithms and the simulation is initialized. During the training the current torch position and angle are transferred from the virtual reality training system to the simulation algorithms where in background the simulation of each time step is executed and its results are cached. After the training has ended, the user can check his training results based on the simulated welding results in a playback view.

The central part of the interface regarding the result visualization in 3D is a mesh that allows the transfer and display of the simulated temperature and geometry information of the weld bead, the weld seam and the work-piece. This mesh is extracted from the simulation results for each simulated time step. To reduce the amount of data, only modified nodes are stored. However, during the testing phase it became clear that the amount of data is too high to be kept in primary storage, so therefore it was decided to store the data in secondary storage and to load it on demand in the playback and analyse view.

Additionally to the 3D results for each time step the following results are provided to allow the virtual training system to determine the quality of the trainees welding results: 2D cross-section of the weld seam including seam area, seam width, reinforcement thickness and penetration depth.

RESULT VISUALIZATION IN FRONIUS VIRTUAL WELDING

Since 2005 Fronius International GmbH together with FH JOANNEUM Gesellschaft mbH is developing a virtual welding training system (Fronius Virtual Welding®) for different welding processes (including GMA) which uses a qualitative weld seam simulation that is not based on numerical welding simulation algorithms.

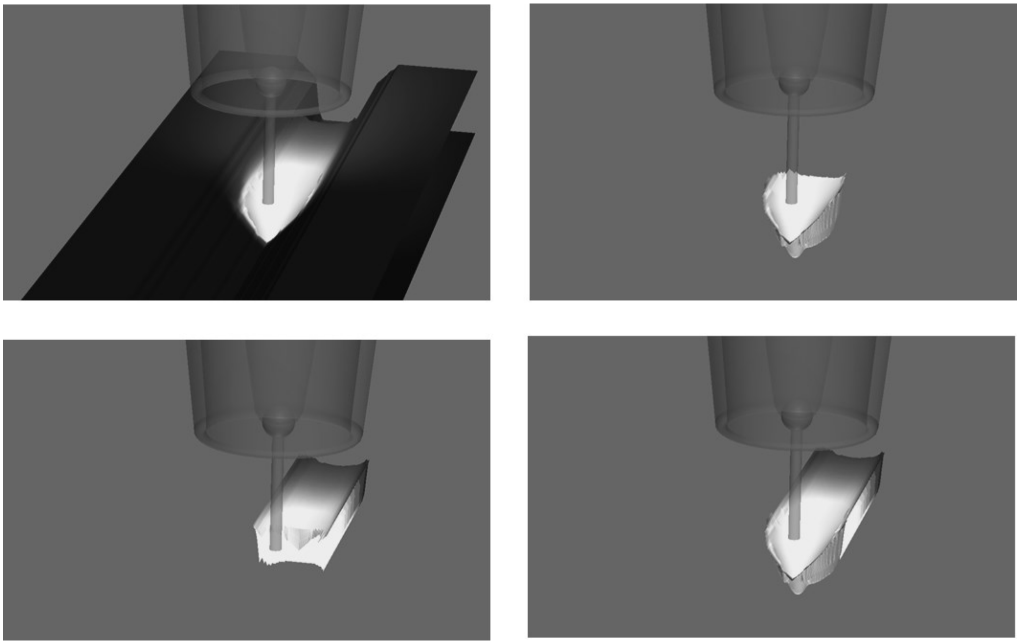

Fig. 10 3D visualization of numerical simulation results calculated by SimWeld® DLL (Top left: overall results, top right: weld bead only, bottom left: weld seam only, bottom right: combined weld bead and weld seam)

To visualize the results of the numerical welding simulation the training system had to be extended by an analysis module that on the one hand shows the calculated weld seam geometry (Fig. 10) and on the other hand visualizes several welding parameters (stick-out, travel and work angle) in an intuitive user interface. The user interface also includes a view of a virtual slice across the weld seam and allows the user to move its view along the weld seam. Fig. 11 shows a screenshot of the analysis module.

Fig. 11 Screenshot of the analysis module as implemented in the Fronius Virtual Welding® training system

CONCLUSION AND OUTLOOK

Based on our understandings regarding the GMA welding process including the current fundamental research results, a simplified but physics based model for numerical welding process simulation has been developed for usage in a virtual reality training system.

This model consists of a transient architecture that is implemented in highly efficient algorithms. This evolution of the SimWeld® model allows a reduction of the calculation time of one iteration from five minutes to less than one second. Further acceleration of the heat transfer calculation can be achieved for example with the Galerkin-Method. Additionally, the next generation of SimWeld® will be based on the newly developed transient architecture, also in cases where simulation time is not a critical condition and slower but more accurate algorithms can be used.

The losses in accuracy due to the extensive reduction of the physical models have been addressed by a calibration of the compensation models based on experimental results. Furthermore, with the consideration of a newly developed model for the heat flux distribution in the cathode area a further improvement in the understanding of the dominating physics has been applied, as well.

For real-time simulations and visualizations in a virtual reality framework, a framerate of at least 25 Hz is mandatory. Currently, this can be achieved only by using high-end computer hardware. The current training system runs on regular PCs and therefore the acceleration of the numerical simulation was not yet able to perform at the desired framerate. Nevertheless, it is a great benefit for the trainee to have the possibility of an in-depth analysis of the training results very shortly after the training.

The project showed that it is possible to integrate a numerical welding process simulation into the Fronius Virtual Welding® training system. In a next step the prototype implementation will be further refined with the goal to provide it to users of the system in the future.

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