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Real time physical simulation for virtual welding training

Fizička simulacija virtuelnog zavarivanja u realnom vremenu

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Abstract

Modern visualization methods facilitate the user a better and deeper understanding of the welding process. Current methods and visualization systems are based on empirical groundwork. A simulation software on the basis of physical models is put at the disposal of the user, which facilitates a visualization of the weld joint geometry and temperature distribution. In this way corrupt weld joints can be detected and handled in advance. This leads to an increase of quality and profitability. For this reason, this approach offers a new benchmark in the world of electric arc technology and sets a basis for a variety of future visions. Physical welding models are so far optimized and reduced in order to facilitate a real-time simulation. The reduction of the models was achieved by a combination of analytical solutions with optimized numerical algorithms for partial differential equations. These measures facilitate the execution of a welding simulation in a very short time. Experimental support (provided by AUDI and Fronius) upon the calibration leads to well validated and reliable results. With modern visualization methods the results are user-friendly presentable. A demonstrator in the form of an expansion of the Fronius Virtual Welding system was set up. The demonstrator contains an offline and an online mode. The offline mode performs the analysis after the welding. The online mode performs the real-time (simulation) analysis during welding. The development is based on results from preceding developments such as Virtual Welding System (Fronius, FH JOANNEUM) and SimWeld Software (RWTH Aachen).

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Rezime

Savremene metode vizualizacije omogućavaju korisniku bolje i dublje razumevanje procesa zavarivanja. Trenutne metode i sistemi vizualizacije se zasnivaju na empirijskim osnovama. Razvijeni simulacioni softveri zasnivaju se na fizičkim modelima, što korisniku olakšavaju vizualizaciju geometrije zavarenog spoja i raspodele temperatura. Na ovaj način eventualno loši zavareni spojevi mogu se unapred otkriti i korigovati. To vodi ka povećanja kvaliteta i profitabilnosti procesa. Ovakav pristup uvodi novo merilo u svetu tehnologije električnog luka i postavlja osnovu za budući razvoj. Fizički modeli zavarivanja su do sada optimizovani i pojednostavljeni kako bi se olakšala simulacija u realnom vremenu. Pojednostavljenje modela postignuto je kombinacijom analitičkih rešenja prenosa toplote sa optimizovanim numeričkim algoritmima za parcijalne diferencijalne jednačine koje opisuju prenost toplote tokom procesa. Ove mere omogućavaju izvođenje simulacije zavarivanja u vrlo kratkom vremenu. Eksperimentalna podrška, koju pružaju firme AUDI i Fronius, omogućavaju kalibraciju modela i dovode do dobijanja proverenih i pouzdanih rezultata. Sa modernim metodama vizualizacije dobijeni rezultati su primenljivi za prezentaciju. Simulacija zavarivanja je unapređena i proširena od strane firme Fronius. Simulator zavarivanja poseduje režime rada "offline" i "online". Oflajn režim vrši analizu nakon zavarivanja. Onlajn režim vrši analizu u realnom vremenu (simulacija) tokom zavarivanja. Razvoj prikazanog modela se zasniva na rezultatima iz prethodno razvijenih modela, poput sistema za virtuelno zavarivanje (Fronius, FH JOANNEUM) i softvera SimVeld (RWTH Aachen).



1. Introduction

Since the 1990ies Virtual Reality Systems have been developed and now they are well known and also well established in many different disciplines, for example in Flight Simulation Training. In welding training such systems are also already state-of-the-art [1], to train beginning welders the skills of manual welding, without using too many resources of time and money or exposing them to dangers.

On the other hand, numerical simulation software for welding process simulation has seen major advances in the recent years, as well. The use of computational simulation methods based on physical models is an established engineering method for the investigation of arc welding processes [2, 3]. It represents an efficient way to find the required welding parameters, especially for unique tasks.

However, often these methods require a large computation time in order to give a result with sufficient accuracy, in some cases they can even take several weeks, even on highperformance computing systems [4]. With the application of the right assumption as well as advanced numerical and computational approaches, the calculation time in the GMAW process simulation platform SimWeld® [5] could be cut to less than one second per iteration, which allows the usage for near real-time welding calculation. This made it possible to combine both computational tools into one Virtual Reality Training system that could give direct feedback and enable a trainee to visualize and learn the effect of different welding parameters. Therefore, based on the virtual welding training system Fronius Virtual Welding®, a visualization module was combined with the near real-time simulation of newly developed transient SimWeld® algorithms.

To our knowledge, there is currently no Virtual Reality Training System for manual welding training on the market, which combines the advantages of virtual reality environments with physics-based simulation results.

2. A transient simulation model of GMA welding for real-time simulation

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 [6-8]), allow to calculate weld seam geometry and heat input and distribution within a few minutes on a standard personal computer. This high calculation speed is mainly due to the replacement of the fluid flows as

1. Uvod

Od 1990-ih godina Sistemi Virtuelne Stvarnosti su razvijani i sada su dobro poznati i primenjuju se u mnogim različitim oblastima kao na primer pri trenaznoj simulaciji letenja. U obuci zavarivanja takvi sistemi su takođe već primenjuju [1], I to za obuku zavarivača I za ovladavanje početnih veština pri ručnom zavarivanju, bez zauzimanja previše resursa vremena i novca, I bez izlaganja opasnostima I eventualnih povređivanja.

S druge strane, softveri za numeričku simulaciju procesa zavarivanja, zabeležili su veliki napredak poslednjih godina. Tkođe primena metoda računarske simulacije zasnovane na fizičkim modelima je omogućila razvoj inženjerska metoda za proučavanje procesa elektrolučnog zavarivanja [2, 3]. To predstavlja efikasan način za određivanje potrebnih parametara zavarivanja, posebno u specifičnim slučajevima. Međutim, često ove metode zahtevaju dugačko vreme proračuna kako bi se dobili rezultati sa dovoljnom tačnosti. U nekim slučajevima mogu potrajati i nekoliko nedelja, čak i sa visokom efikasnošću računarskih sistema [4]. Sa primenom pravih pretpostavku kao i uz primenu naprednih numeričkih I računarskih pristupa, vreme proračuna pri simulaciji MAG procesa pri primeni platforme za simulaciju procesa SimVeld® [5], bi mogla da bude smanjena na manje od jedne sekunde po iteraciji, što omogućava upotrebu za simulaciju zavarivanja u skoro realnom vremenu. Ova kombinacija oba računarska alata u jedan Sistem za obuku u virtuelnoj stvarnosti, može dati direktne povratne informacije i omogućiti korisniku da vizualizuje i nauči o efektima različitih parametara zavarivanja. Prema tome, na osnovu sistema za virtuelno zavarivanje Fronius Virtual Velding®, a modul za vizuelizaciju je kombinovan sa gotovo realnim vremenom simulacija novorazvijenog algoritma SimVeld®-a. Prema našim saznanjima, trenutno ne postoji na tržištu virtuelni sistem obuke za ručno zavarivanje, koji kombinuje prednosti virtuelne stvarnosti okruženja sa rezultatima simulacije zasnovanim na fizici.

2. Simulacioni model MAG zavarivanja za simulaciju u realnom vremenu

Simulaciona grupa Instituta za zavarivanje i spajanje sa RWTH Univerziteta u Ahenu (ISF) vršila je istraživanje procesa elektrolučnog zavarivanja radi formulisanja fizičkih modela koji bi nakon uvođenja u softver (SimVeld® - Softver za Simulaciju Procesa Zavarivanja [6-8]), omogućili izračunavanje geometrije zavarenog spoja i unosa I raspodelu toplote u roku od nekoliko minuta na standardnom ličnom (PC) računaru. Ovako velika brzina proračuna uglavnom je posledica zamene



well as magnetohydrodynamic effects in the weld pool and the arc area by reduced compensation algorithms.

The model architecture of the simulation algorithms implemented in SimWeld® are based on the given welding parameters, material properties and power source control algorithms. The models are calculating an average heat and mass input as well as an arc pressure distribution for a defined welding time, as well as weld pool and seam geometry the heat flow within the complete macroscopic area of the workpiece. The newly developed transient model architecture is based on the steady-state algorithms of SimWeld®, but allows the transient execution of the GMA welding process simulation. The calculation time for each transient iteration was reduced to less than one second, depending on the used computer hardware, by optimizing the algorithms and reducing the model dimensions.

However, for true real-time simulation a reduction of the calculation time to less than 40 ms or 25 Hz is required, which corresponds to the frequency of human visual perception. This would require another speed up of the factor of 25, which is still a research goal and now within reach. The applied models are also able to react on current pulses and short circuits, as well as the unique movement of the torch, which is typical for a manual welding procedure. The resulting output, which is obtained, includes the shape of the weld pool and weld bead Fig. 1, as well as the temperature fields in the work piece and the area and thermocycles in the HAZ.

mešanja tečne faze u zavarivačkom tečnom kupatilu, kao i magnetohidrodinamičke efekte, u oblast delovanja električnog luka jednostavnijim algoritmima. Arhitektura modela algoritama simulacije implementirani u SimWeld®, zasnovani su na zadatim parametrima zavarivanja, osobinama materijala i algoritmima kontrole izvora napajanja. Modeli izračunavaju prosečnu toplotu i unos mase kao i raspodele pritiska električnog luka za definisano vreme zavarivanja. Takođe izračunavaju veličinu metalne kupke i geometriju zavarenog spoja u makroskopskoj oblasti radnog komada. Novorazvijena arhitektura prelaznog model se zasniva na stacionarnom algoritmu SimWeld®, ali omogućava obavljanje simulacije MAG procesa zavarivanja. Vreme izračunavanja za svaku iteraciju je smanjena na manje od jedne sekunde, i u zavisnosti od korišćenog računarskog hardvera, kroz optimizaciju algoritama i smanjenje dimenzija modela. Međutim, za stvarnu simulaciju u realnom vremenu zahteva se smanjenje vremena proračuna na manje od 40 ms ili 25 Hz, što odgovara frekvenciji vizuelne percepcije čoveka. To bi zahtevalo još jedno ubrzanje faktorom 25, što je još uvek cilj istraživanja i sada je skoro postignuto. Primenjeni modeli su takođe su u stanju da reaguju na strujne impulse i kratke spojeve, kao i kretanje gorionika tipično za procedure ručnog zavarivanja. Dobijeni rezultati obuhvataju definisanje oblika tečnog kupatila metala šava i nadvišenje metala vara, kao što je prikazano na Slici 1. Takođe dobijaju se i temperaturna polja u radnom komadu kao i površina i termalni ciklus u zoni uticaja toplote (ZUT).

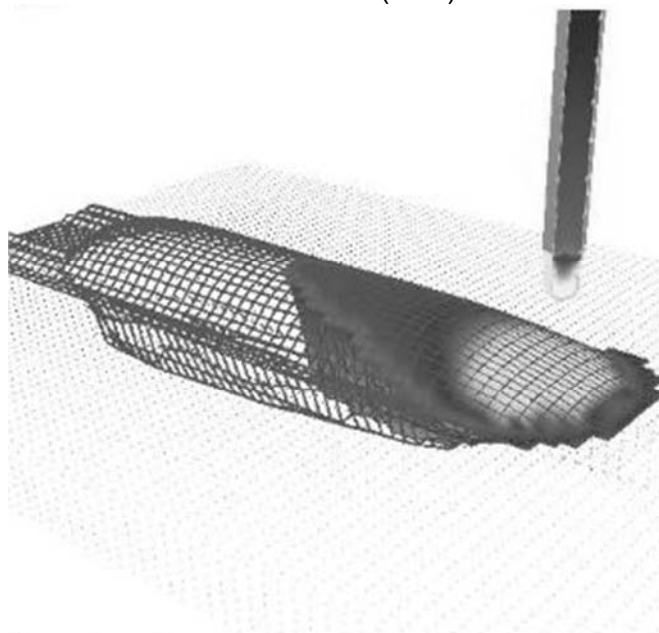


Figure 1. Example of the result of a transient Simulation in SimWeld®
Slika 1. Primer rezultata simulacije zavarivanja programom SimWeld®



3. Comparison of simulated and experimental results

The simulation algorithms that were developed 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 physics-based virtual welding results.

In order to reach for the goal of real-time simulation, simulation speed was favoured over the accuracy of the simulation results. For this reason, a validation of the results was necessary and for this purpose welding experiments were executed at Fronius and Audi, including transient measurement of current and voltage as well as crosssections of the weld seam.

The resulting comparison is shown in Fig. 2, which shows that the deviations in the calculated heat input were deviating at about 10 % from the experimental result. However, when considering that the calculation is performed at an iteration timestep of 25 Hz, which means that the calculation will be performed many times during an actual training weld. Therefore it is not necessary to achieve a correct result at every iteration, but it is rather important that the general trend of the process can be captured and displayed. Therefore, the resulting accuracy is considered to be sufficient.

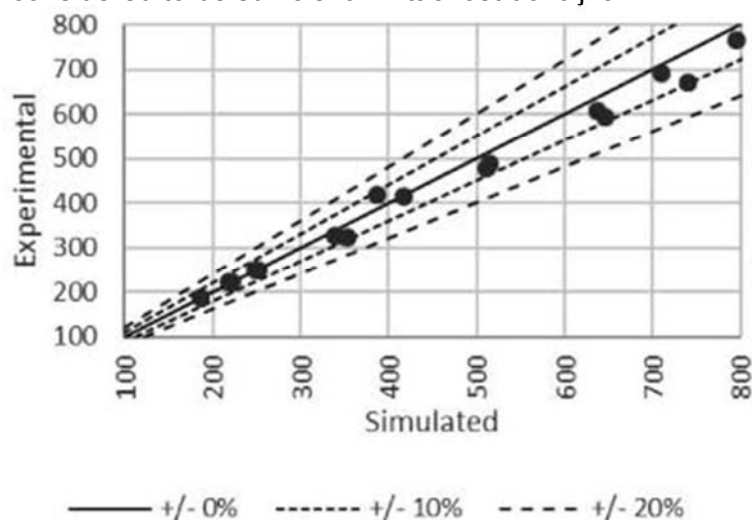


Figure 2. Comparison of experimental and simulated heat input in J/mm, taking into account an efficiency factor of approx. 80%

Slika 2. Poređenje eksperimentalnog i simuliranog unosa toplote u J/mm, uzimajući u obzir faktor efikasnosti od oko 80%

4. 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.

3. Poređenje simuliranih i eksperimentalnih rezultata

Razvijeni algoritmi simulacije su tako projektovani da omogućavaju brzi proračun koji može da se primeni za obuku u uslovima virtuelne stvarnosti. Cilj je omogućavanje korisniku primenu prednosti rezultata virtuelnog zavarivanja zasnovanih na zakonima fizike.

Da bi postigli cilj simulacije u realnom vremenu, brzina simulacije favorizovana je u odnosu na tačnost rezultata simulacije. Zbog toga je validizacija rezultata bila neophodna i u tu svrhu su izvršeni eksperimenti zavarivanja u Froniusu i Audiju, uključujući i merenje struje i napona kao i preseka zavarenih spojeva.

Dobijeno poređenje rezultata prikazano je na slici 2, koje pokazuje da su odstupanja u izračunatoj unešenoj toploti odstupaju od oko 10% od eksperimentalno dobijenih rezultata. Međutim, kada se uzme u obzir da se proračun vrši pri koraku vremenske iteracije od 25 Hz, što znači da će proračun biti izvedeni mnogo puta tokom stvarnog treninga zavarivanja. Zbog toga nije potrebno postići tačan rezultat za svaku iteraciju, ali je prilično važno da se može uhvatiti i prikazati opšti trend procesa. Stoga se smatra da je rezultirajuća tačnost dovoljna.

4. Rezultati vizualizacije kod Fronius Virtual Welding®

Od 2005. godine Fronius International GmbH zajedno sa FH JOANNEUM Gesellschaft mbH razvija virtuelni sistem obuke za zavarivanje (Fronius Virtual Velding®) za različite postupke zavarivanja (uključujući MAG postupak) koji koristi kvalitativne simulacije šava na kojoj se ne zasniva na algoritmima numeričke simulacije zavarivanja.



To visualize the results of the numerical welding simulation the training system was extended by an analysis module that on the one hand shows the calculated weld seam geometry (Fig. 3) and on the other hand visualizes several welding parameters (stickout, travel and work angle) in an intuitive user interface.

The user interface will also include a view of a virtual slice across the weld seam and allows the user to move its view along the weld seam. Fig. 4 shows a prototype of the analysis module, where as an example, the critical areas of the resulting weld seam are marked with different colors (green, red and yellow), indicating, for example, that the torch angle was insufficient at this position or other such issues.

Da bi se vizualizovali rezultati numeričke simulacije zavarivanja sistem obuke je proširen analizom modula koji s jedne strane prikazuje izračunatu geometriju šava, prikazano na Slici 3, a sa druge strane vizuelizuje nekoliko parametara zavarivanja (dodavanje žice, kretanje i radni ugao) jednim intuitivnim korisničkim interfejsom.

Korisnički interfejs će takođe sadržati prikaz virtuelnog preseka zavarenog spoja, čime se omogućava korisniku da pomeri pogled duž linije zavarivanja. Slika 4 prikazuje prototip modula za analizu, gde su kao primer označena kritična područja rezultirajućeg šava, označena različitim bojama (zelena, crvena i žuta), što ukazuje, na primer, da gorionik nije bio pod dovoljnim uglom u ovom položaju ili je u pitanju neka druga nepravilnost.



Figure 3. 3D visualization of numerical simulation overall results calculated by SimWeld® DLL in the Fronius Virtual Welding® playback view.

Slika 3. 3D vizuelizacija numeričke simulacije sa rezultatima izračunatim programom SimWeld® DLL reprodukovani na simulatoru Fronius Virtual Welding®



Figure 4. Prototype of the analysis module as developed for the Fronius Virtual Welding® training system.

Slika 4. Prototip modula za analizu kako je razvijen za sistem obuke Fronius Virtual Welding®.



5. Conclusion and outlook

For the next generation of the Fronius Virtual Welding® a reduced physics-based model for numerical welding process simulation was developed. The model consists of a transient architecture that is implemented in highly efficient algorithms.

The losses in accuracy due to the extensive reduction of the physical models have been addressed by performing a validation on experimental data with satisfactory results.

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 highend 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, the trainee can still benefit from the possibility to have an indepth analysis of the training results very shortly after the training.

Such a digitalized welding training allows to transfer more information to the learner in a shorter time. It represents therefore a revolution in the way welding can be taught, as the education of not only the empirical but also the physical knowledge is more intuitive and efficient. From this, a massive enhancement of the quality of the education is to be expected, while requiring the same or even less time, as well as less material consumption.

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5. Zaključak i budući rad

Za sledeću generaciju virtuelnog zavarivanja Fronius Virtual Welding®, razvijen je pojednostavljen fizički model za numeričku simulaciju postupka zavarivanja. Arhitektura modela se sastoji od implementiranog visoko efikasnog algoritma. Smanjena tačnosti usled opsežnog smanjenja fizičkih modela su postignuta izvođenjem validacije eksperimentalnih podataka i dobijanjem zadovoljavajućih rezultata. Za simulacije i vizualizacije u stvarnom vremenu u virtuelnom prikazu stvarnosti, obavezna je frekvencija proračuna sa učestalošću od najmanje 25 Hz. Trenutno se to može postići samo upotrebom brzih i velikih računarskih hardvera. Trenutni sistem obuke koristi klasične personalne računare i samim tim brzina numeričke simulacije nije u stanju da postigne željenu brzinu proračuna i simulacije. Ipak, polaznik obuke i dalje može imati koristi od mogućnosti analize rezultata vrlo brzo nakon treninga. Prikazani digitalizovani trening izvođenja procesa zavarivanja omogućava prenos mnogo više informacija korisniku u kraćem vremenskom intervalu. Samim tim ova metodologija predstavlja revoluciju u načinu na koji se može naučiti zavarivanje, tako da su dobijena znanja uviđanjem i opažanjem i više nisu samo empirijska već se stiču znanja o fizičkim procesima koji se odvijaju tokom zavarivanja. Ovo veliko unapređenje kvaliteta obrazovanja, zahteva jednako ili kraće vreme uz istovremeno manje materijalne troškove.

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