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Virtual Manual Arc Welding by Real-Time Process Simulation for an Effective Training

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ABSTRACT: Training is usually carried out throughout traditional methods which impose enormous costs. Virtual reality is one of the most suitable methods that has been presented in this application and improves many of the weak points of traditional training such as high cost of welding. Previous studies were conducted on virtual welding with the use of virtual reality techniques in welding training. The novelty of this article is that uses Kinect for tracking and Adaptive meshing for thermal analysis. The dimension of workpiece is 70x50x10 and the material is low carbon steel. The user performs real-time welding in the virtual environment by moving the electrode clamp. Since process parameters like current, hand motion speed, arc length, and welding voltage make changes in generated heat, and color of molten-solid zone, a graphic interface updates the color in each part of the model. The process is modeled in two different ways of fixed and adaptive mesh finite element approaches which manifests good precision and calculation of speed, respectively. All calculations in the simulation environment and the thermal analysis engine performed in the C# program. One of the positive features of the simulator is self-learning. A novice welder could take enough time to learn the manual arc welding simulator without any extra cost or danger. This simulator provides a good training ability to control the welding

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1. INTRODUCTION

Welding is one of the main processes of production, which assumes the task of permanently connecting parts. Nowadays welding is the most pertinent and industrialized method among assembly methods and as a result, the training procedure is one of the most important and useful trainings that devotes research investigations. At the same time, welding training is one of the most expensive and difficult ones due to safety issues and total costs, which corresponds more or less to every type of welding. Therefore virtual reality is one of the most suitable methods that has been presented in this application so far and improves many of the weak points of traditional training such as high cost of welding (such as consumables and electricity), low safety, and learning speed, and poor quality training. In this method, the user holds an arc welding clamp and visualizes the virtual workpiece on a computer screen. The Position and Orientation (POS) of the electrode tip is calculated by a motion tracker and a suitable algorithm used for welding simulation is thereby fed.

Wu et al. [1] developed the oldest welding simulator where they investigated the amelioration of training by a welding simulator. The test coverage included 220 students investigated during two years and demonstrated promising results in terms of time and cost. Mavrikos al. [2] developed a 3D welding simulator for MIG/MAG methods with the possibility of adjusting the process parameters such as gas, electrode, electrical current, and gas flow. Welding speed, torch distance, and torch angle were used in the evaluation score. Porter et al. [3] used a back-propagation algorithm in artificial intelligence to create welding seam form. In 2009, Dongling and his colleagues [4] modeled the welding heat distribution by ANSYS which provided offline but precise results. Kobayashi et al. [5] proposed a training system of manual arc welding by means of mixed reality techniques. The system consists of an HMD and a real electrode in real and the weld arc with sparks in the virtual world. Asai et al. [6] worked on visualization and digitization of welder skills during training through 4 cameras and within comparison against an expert. Different types of GTAW, GMAW, and SMAW were successfully tested on the proposed simulator.

Welding parameters have been widely taken into account on simulator in reference [7]. Yang et al. [8] developed a virtual welding system with 3D interaction for simulating the bead shape by the neural network . Jen Yap and his colleagues [9] proposed a MAG welding training system to permit the control of arc length, electrode angle, and hand motion speed for reducing the real process costs. Petra and Axel [10] studied the influence of augmented and virtual reality on the improvement of welding training, letting the user observe the change in pool and seam geometry. The simulator developed by Yunus [11] demonstrated a considerable amelioration in the user's skills.

The main part of a simulator called physics engine

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calculates in real-time the thermal cycle and weld geometry by a numerical method. Xie [12] introduced a finite difference approach to consider the parameters like feed speed and electrode diameter. Fast and his colleagues [13] presented a neural network method to estimate the quality and geometrical shape of weld. Benson et al. [14] described an innovative virtual welding system and the investigations are ongoing in this field. Moradi et al. [15]investigated numerical and experimental laser welding. They used ABAQUS for thermal analysis. They showed that this program is capable of calculating the temperature at any nodal point in the material.

Based on similar works and due to the increasing interest in welding education, this paper investigates the different aspects of an efficient simulator. This simulator is principally enforced by accessible and non-consuming components that permit a novice to repeatedly practice the manual arc welding process. However, the main innovation concerns a precise and rapid calculation method for heat distribution in workpiece. It is based on a convenient finite element method that updates in real-time considering the conditions of the process.

The following section introduces thermal analysis of welding process considering a moving heat source by using finite element method. Thereafter presents a new finite element model based on adaptive meshing to achieve necessary speed and precision. At last, the results of two models are compared and the simulator effect on the user's skill is demonstrated. The simulator components and the graphic part are also explained.

2. PRINCIPLE AND METHODOLOGY

As described below, four parameters of the arc length, hand motion speed, motion angle, and welding angle essentially determine welding quality [16]:

a. Arc length corresponds to the vertical distance between the electrode tip and the workpiece surface, as shown in Fig. 1.

b. Hand motion speed corresponds to the speed at which the welding torch moves upon the workpiece surface.

c. Motion angle is the angle between the electrode and the vertical (y) axis considering Fig. 2.

d. Welding angle is the angle between the electrode and the z-axis (Fig. 2), which lies in the plane of the workpiece surface and perpendicular to the motion direction.

2.1. Virtual Reality Systems

In a virtual reality system, a user experiences the immersion in a virtual environment and interacts with the virtual objects with some of the five senses in real-time. Virtual reality uses a graphical simulator to provide a realistic scene of the process in real-time, i.e. the computer uses updated inputs to modify the scene at a very high speed. One of the most important components of the virtual environment is visual interface, which displays rendered objects. The visual interface is equipped with position and orientation sensors that track human POS and the view direction. Sequentially the immersion is created and the virtual environment resembles the real one by utilizers. Apart from visual sense, the user usually perceives the voices transmitted through sound interface [17].

The combination of virtual reality with the e-Learning system has created a completely immersive virtual world. Different types of such systems are previously proposed. The Lincoln Electric VRTEX 360 is a virtual reality training system that enables welders to be trained better, faster and at a lower cost. The system accurately scores the weld, visually indicates proper versus improper movements and indicates what welding defects resulted from any improper techniques. Once a weld is complete, the student could perform a virtual bend test on the weld coupon [18]. Soldamatic is another educational tool for welding training that uses interactive simulation together with augmented reality. It offers a wide range of features including configuration to the different weld processes and in turn, to different training courses – from the initial to the most advanced levels [18]. The Arc+ Welding Simulator is a training tool that powers lifelike virtual welding practice. The ARC+ system platform was first introduced in Canada through companies and welding schools and has now been commercialized [18].

2.2. Thermal Analysis

Welding is a time-dependent process and the related heat transfer is analyzed by a transient approach to generate the temperature distribution on the workpiece. The governing equation for temperature T in x, y, and z directions is given by Eq. (1), as in reference [19]. Fig. 3 schematically shows the heat transfer problem.

$$-\left(\frac{\partial R_x}{\partial x}+\frac{\partial R_y}{\partial y}+\frac{\partial R_z}{\partial z}\right)+Q\left(x,y,z,t\right) = rC\,\frac{\partial T\left(x,y,z,t\right)}{\partial t} \quad (1)$$

The model is then completed by introducing the Fourier heat conduction laws applied as follows in Eqs. (2) to (4).

where Kx, Ky, Kz in these equations and ρ and C in Eq. (1) are time-dependent parameters that cause non-linearity in heat transfer equations. Replacing the Eqs. (2) to (4) in Eq. (1) gives:

$$R_x = -K_x\,\frac{\partial T}{\partial x} \quad (2)$$

$$R_y = -K_y\,\frac{\partial T}{\partial y} \quad (3)$$

$$R_z = -K_z\,\frac{\partial T}{\partial z} \quad (4)$$

where Kx, Ky, Kz in these equations and ρ and C in Eq. (1) are time-dependent parameters that cause non-linearity in heat transfer equations. Replacing the Eqs. (2) to (4) in Eq. (1) gives:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial T}{\partial z}\right) +Q(x,y,z,t)=\rho c \frac{\partial T(x,y,z,t)}{\partial t} \quad (5)$$

2.2.1. Classical Solution Of The Equation

First, a general solution based on Galerkin finite elements method, as described in Eq. (6) is used to solve the heat transfer equation.

$$\int N^T \left[\frac{\partial}{\partial x}\left(K_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial T}{\partial z}\right) +Q(x,y,z,t)-rc\frac{\partial T(x,y,z,t)}{\partial t}\right]=0 \quad (6)$$

By solving this equation and replacing the shape function, the terms of Eq. (7) are achieved.

$$C\dot{T}+\left(K^{cond}+K^{conv}+K^{rad}\right)T =Q^{inp}+Q^{conv}+Q^{rad} \quad (7)$$

In this equation, C, K^{cond}, K^{conv} and K^{rad} are matrices of capacity, conductivity stiffness, convection stiffness and radiation stiffness, respectively. Q_S, Q^{conv} And Q^{rad} represent the amount of heat due to conduction, convection and radiation, respectively. These parameters are expressed as follows in Eqs. (8) to (14).

$$C=\sum_e \int N_e^T rcN_e dv \quad (8)$$

$$K^{cond}=\sum_e \int B_e^T KB_e dv \quad (9)$$

$$K^{conv}=\sum_e \int N_e^T h_{conv} N_e dS \quad (10)$$

$$K^{rad}=\sum_e \int N_e^T h_{rad} N_e dS \quad (11)$$

$$Q_s=\sum_e \int N_e^T q_s dS \quad (12)$$

$$Q^{conv}=\sum_e \int N_e^T h_{conv} N_e \; T_0 dS \quad (13)$$

$$Q^{rad}=\sum_e \int N_e^T h_{rad} N_e \; T_0 dS \quad (14)$$

In a compact form, Eq. (7) is transformed into Eq. (15).

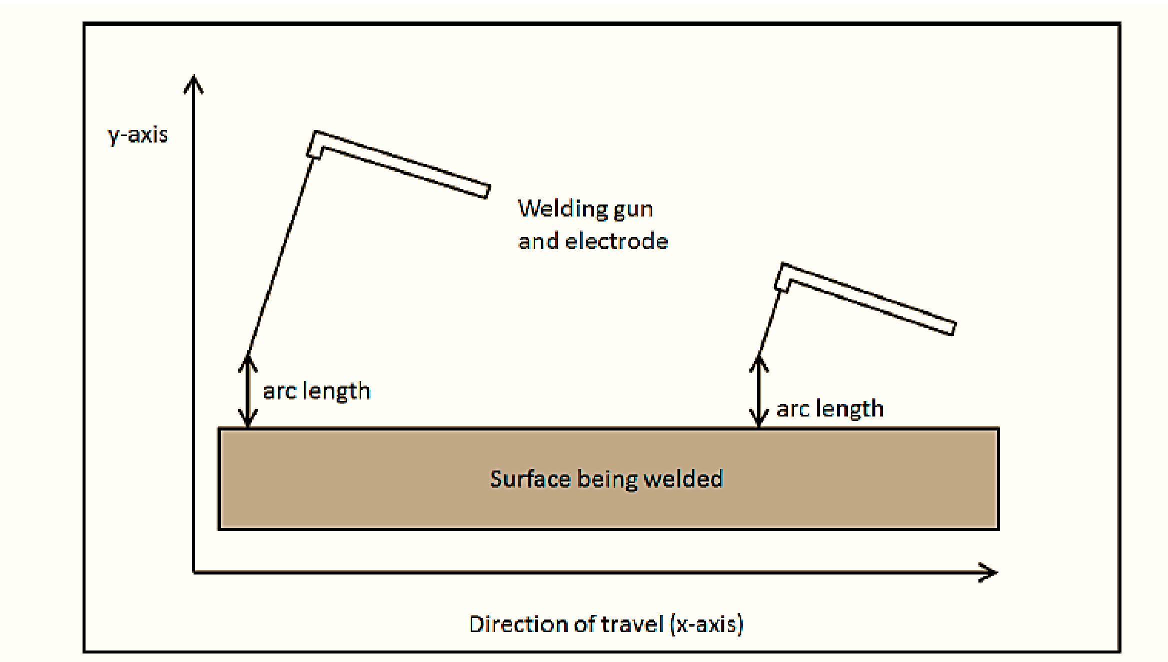


Fig. 1. Welding arc length [16]

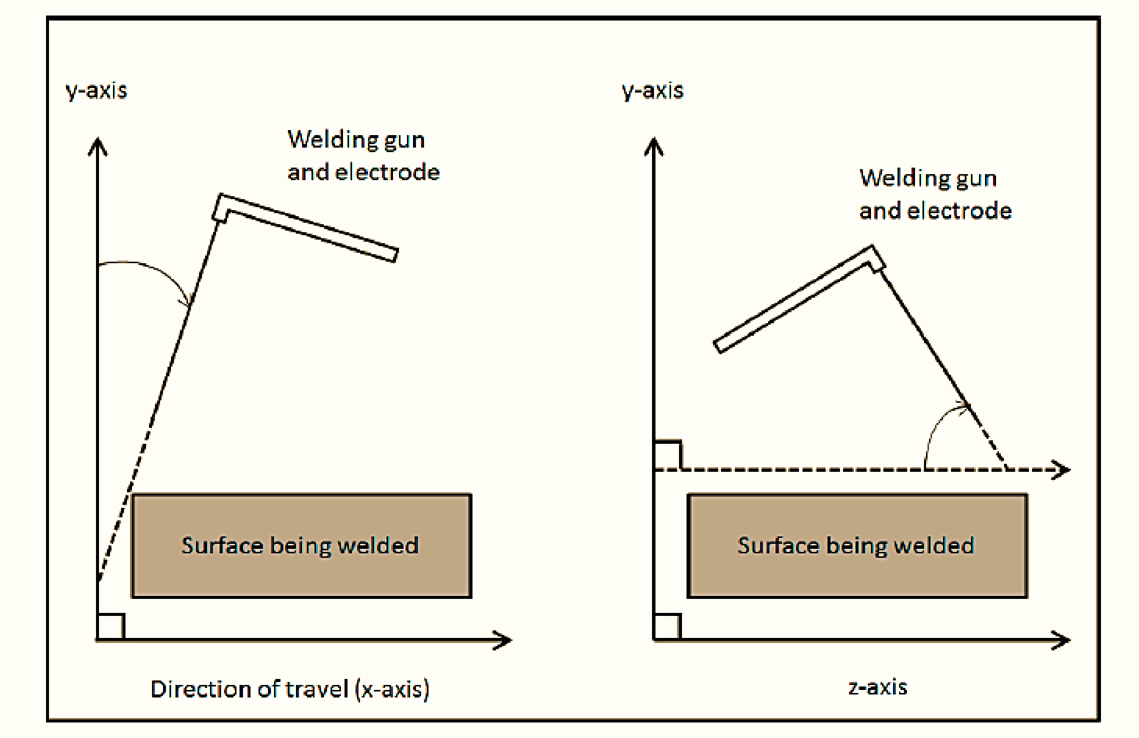


Fig. 2. Motion and welding angles [16]

$$C\dot{T} + KT = Q \tag{15}$$

Eq. (16) describes a solution based on Crank-Nicolson method, given for the above Eq. (15).

$$\left(C + \frac{KDt}{2}\right)T_{i+1} = \left(C - \frac{KDt}{2}\right)T_i + \left(\frac{Q_i + Q_{i+1}}{2}\right)Dt \tag{16}$$

Given the values obtained at each step and by replacing in Eq. (16), the temperature will be obtained at each node of the model.

2.2.2. Heat Source

Thermal arc distribution has been modeled so far by different approaches so that each approach completes the previous ones and eliminates imperfections [20]. Table 1 gives a summary description of pertinent approaches which are applied to model the heat distribution in arc welding process.

2.2.3. Adaptive Meshing

Once a model is selected for the simulator physics engine, a numerical solver has to be adapted to update the thermal distribution. In finite element, several meshing methods have been applied during the years to this end. Structural meshing generally follows a classical trend and the mesh refinement continues until the desired precision is achieved, regardless of the calculation time. Thus the main finite element analysis problem is the meshing procedure in order to obtain the results with the required precision and least analysis time. When the elements are refined, the result's precision is increased, but it requires a great analysis time which is not compatible with a simulator. Therefore, selected meshing pattern should provide precision and calculation rapidity at the same time. The critical issue in this context is the variation of mesh size from the workpiece's edges toward welding area or weld seam. Taking a very high gradient along the weld seam, the heat distribution is very sensitive and reaches the highest density in this zone in comparison with the other parts. Consequently, the selected pattern should reduce the meshing size around the welding area. The other parts of the workpiece could be modeled with larger elements and allow to calculate the heat distribution faster. Fig. 4 shows that the meshing size enlarges gradually from the seam towards the borders.

Then a finite element analysis of temperature distribution is performed based on the proposed meshing by coding under *C#*. The results for two areas of upon the weld seam and around the weld seam are validated against ABAQUS in Fig. 5 and Fig. 6. Convenient correspondence is observed for both of the results.

Despite precise results for the mentioned meshing type, the calculation speed is unfortunately too slow and the so-called predetermined *fixed meshing* does not satisfy real-time requirements of the simulator. In this article, instead of fixed meshing pattern, an *adaptive meshing* method is proposed to adjust each element size to a proper value during the simulation based on the electrode position and orientation.

Table 1. General overview of different thermal models

Thermal model	Equation	Description
Rosenthal	Assumes either a point, line, or plane source of heat	Serious error for temperatures in or nearby the fusion and heat-affected zones
Disc heat source (Pavelic model)	$q_{(r)} = q_{(0)} e^{-cr^2}$	Need for an effective volume source
Friedman, Krutz and Segerlind	$q(x, y) = \frac{3Q}{pc^2} e^{-3\frac{x^2}{c^2}} e^{-3\frac{x^2}{c^2}}$	Where the effective depth of penetration is small, the surface heat source model has been quite successful
Hemispherical Gaussian Distribution	$q(x, y, x) = \frac{6\sqrt{3}Q}{pc^{c^{3p}\sqrt{p}}} e^{-3\frac{x^2}{c^2}} e^{-3\frac{y^2}{c^2}} e^{-3\frac{x^2}{c^2}}$	A hemispherical source is not appropriate for welds that are not spherically symmetric
Ellipsoidal Volume Source	$q(x, y, z, t) = \frac{6\sqrt{3}Q}{abcp\sqrt{p}} \left(e^{-3\frac{x^2}{a^2}} e^{-3\frac{y^2}{b^2}} e^{-3\left[z+v(t-t)\right]^2/c^2} \right)$	the temperature gradient in front of the heat source was not equal to rear
Double Ellipsoidal Power Density Distribution	Front of source : $q(x, y, z, t) = \frac{6\sqrt{3}f_f Q}{abcp\sqrt{p}} \left(e^{-3\frac{x^2}{a^2}} e^{-3\frac{y^2}{b^2}} e^{-3\left[z+v(t-t)\right]^2/c^2} \right)$ Rear quadrant of source : $q(x, y, z, t) = \frac{6\sqrt{3}f_r Q}{abcp\sqrt{p}} \left(e^{-3\frac{x^2}{a^2}} e^{-3\frac{y^2}{b^2}} e^{-3\left[z+v(t-t)\right]^2/c^2} \right)$	A more complete model than other ones

This technique simultaneously optimizes the precision and speed of the analysis. Indeed the analysis precision is more critical on the zone of the workpiece which interacts with the heat source, i.e. under the electrode position. Thereby the meshing gets the finest values just close to this moving area and the other zones take advantage of course elements.

In this method, no preliminary information is available for meshing and several steps should be carried out before getting the final pattern. Adaptive meshing includes two main parts: error evaluation and mesh refinement.

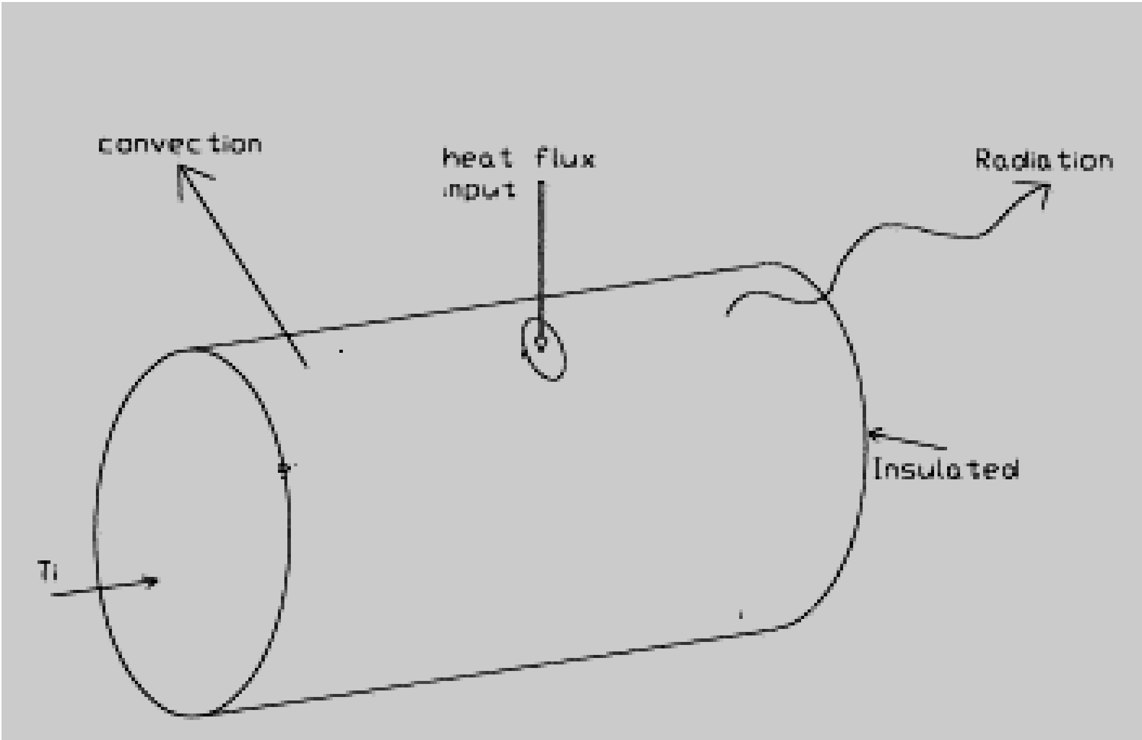


Fig. 3. Schematic of the three-dimensional heat transfer problem

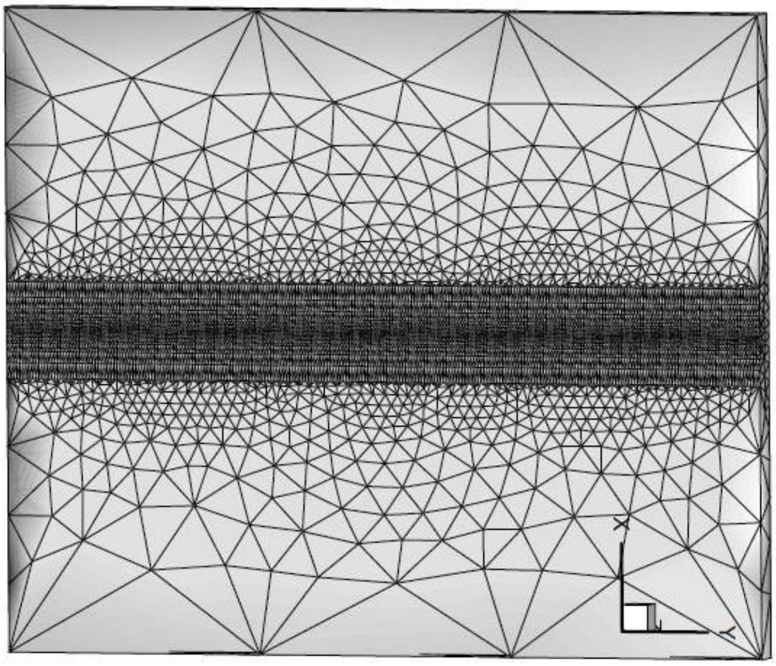


Fig. 4. Fixed meshing pattern along the weld seam

Former part determines if one mesh contains sufficiently precise information or refinement is needed in order to attain the desired precision level. This evaluation is then used to modify the mesh accordingly in the latter part. The error will be relatively reduced through this procedure [21].

The temperature gradient and distance from the electrode are considered as two main criteria for error evaluation in this article. Once the electrode moves toward one *parent element* (primary element before it is refined) in the initial pattern, disequilibrium in the temperature gradient causes the transformation of the parent element to some finer ones. As presented in Fig. 7 four refinement rules are proposed in adaptive meshing method [22]:

a) h-refinement, change in mesh size
b) p-refinement, change in mesh order
c) hp-refinement, a combination of a and b
d) r-refinement, nods are constant in number but variable in positioning coordinates

Gharebaghi used an h-refinement adaptive method in his paper [23] and evaluated the error in a shear crack model in his paper. In another investigation [24], change of element size is proposed by three methods as follows.

- First method: A tetrahedron with only one refined edge is bisected (Fig. 8(a)).
- Second method: A tetrahedron with three refined edges of the same triangular face is divided into four tetrahedrons (Fig. 8(b)).
- Third method: A tetrahedron with two refined edges is divided into three or four tetrahedrons as (Fig. 8(c)).

The second method is used in this article considering the ease of modeling rule and calculation speed. The workpiece is a metal sheet and the meshing uses tetrahedron elements. A reference model is built in ABAQUS software which includes 1,636 nodes and 5,185 elements. In the adaptive mesh method, the number of nodes and elements are 120 and 280, respectively as shown in Fig. 9.

The results of the mentioned finite element analysis for thermal cycle of seam weld are studied by using the fixed and the adaptive mesh methods.

Fig. 10 demonstrates that the temperature peak is exactly the same for both curves. But in two-side proximities, just before and after the peak, the adaptive mesh does not derive the values of the fixed mesh. The main reason is the lack of enough element number in the zones where the temperature gradient is rather high.

Two following diagrams in Fig. 11 and Fig. 12 give a comparison of the thermal cycles respectively calculated beside and far from the weld seam for two meshing types. For a similar reason, when the distance of the analysis point

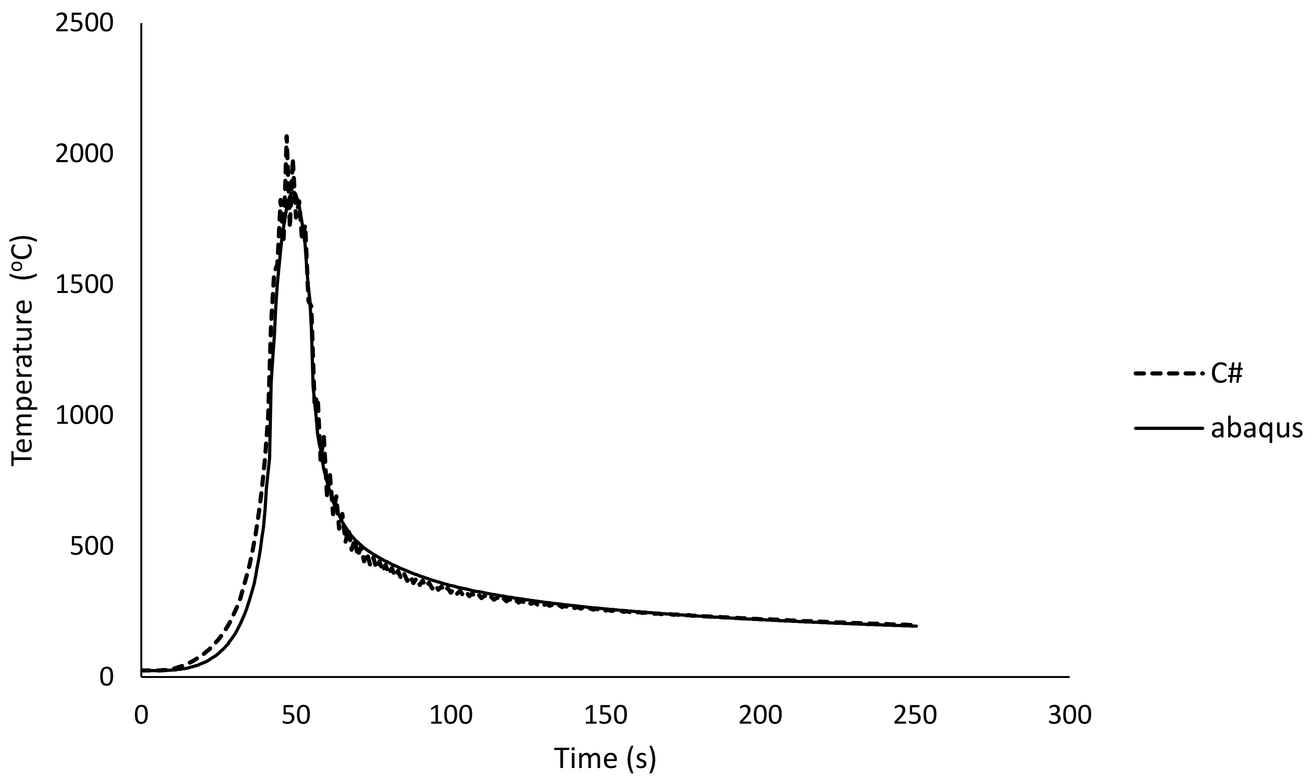


Fig. 5. Comparison of thermal cycle on weld seam calculated by C# codes against ABAQUS

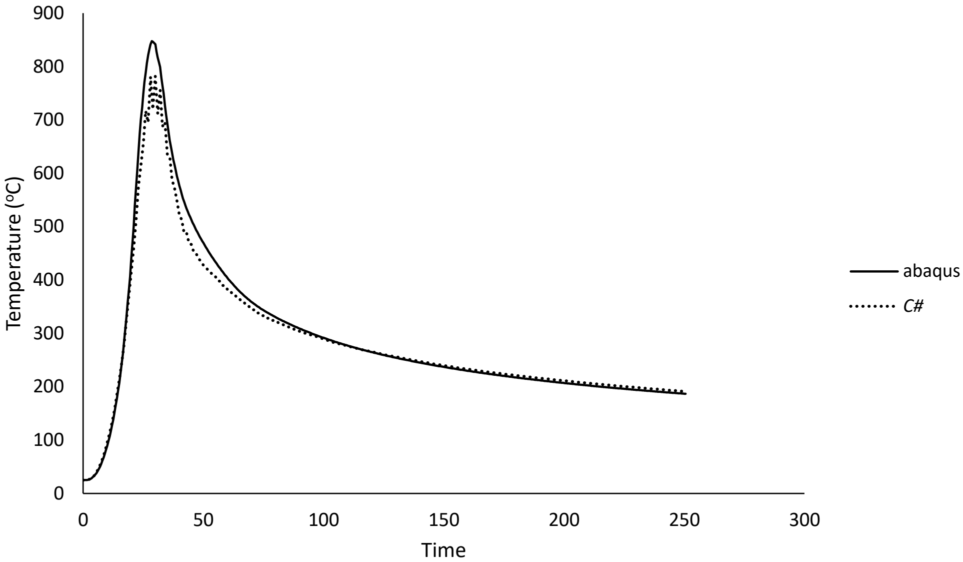


Fig. 6. Comparison of thermal cycle beside weld seam calculated by C# codes against ABAQUS

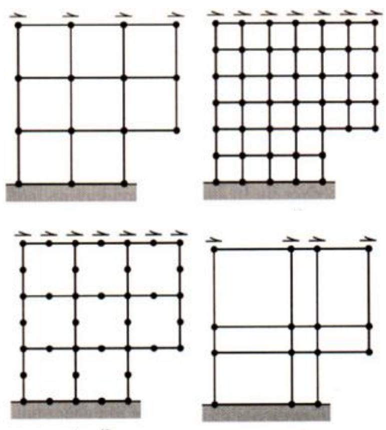


Fig. 7. Adaptive meshing methods, a) Primary element, b) h-refinement method, c) p-refinement method, d) r-refinement method [22]

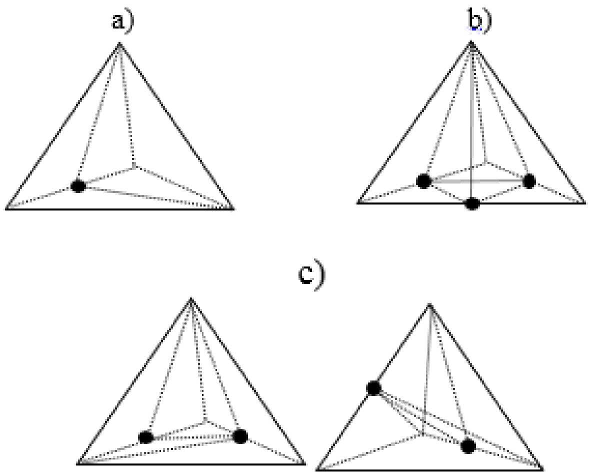


Fig. 8. Methods of change in element size, a) First method, b) Second method, c) Third method

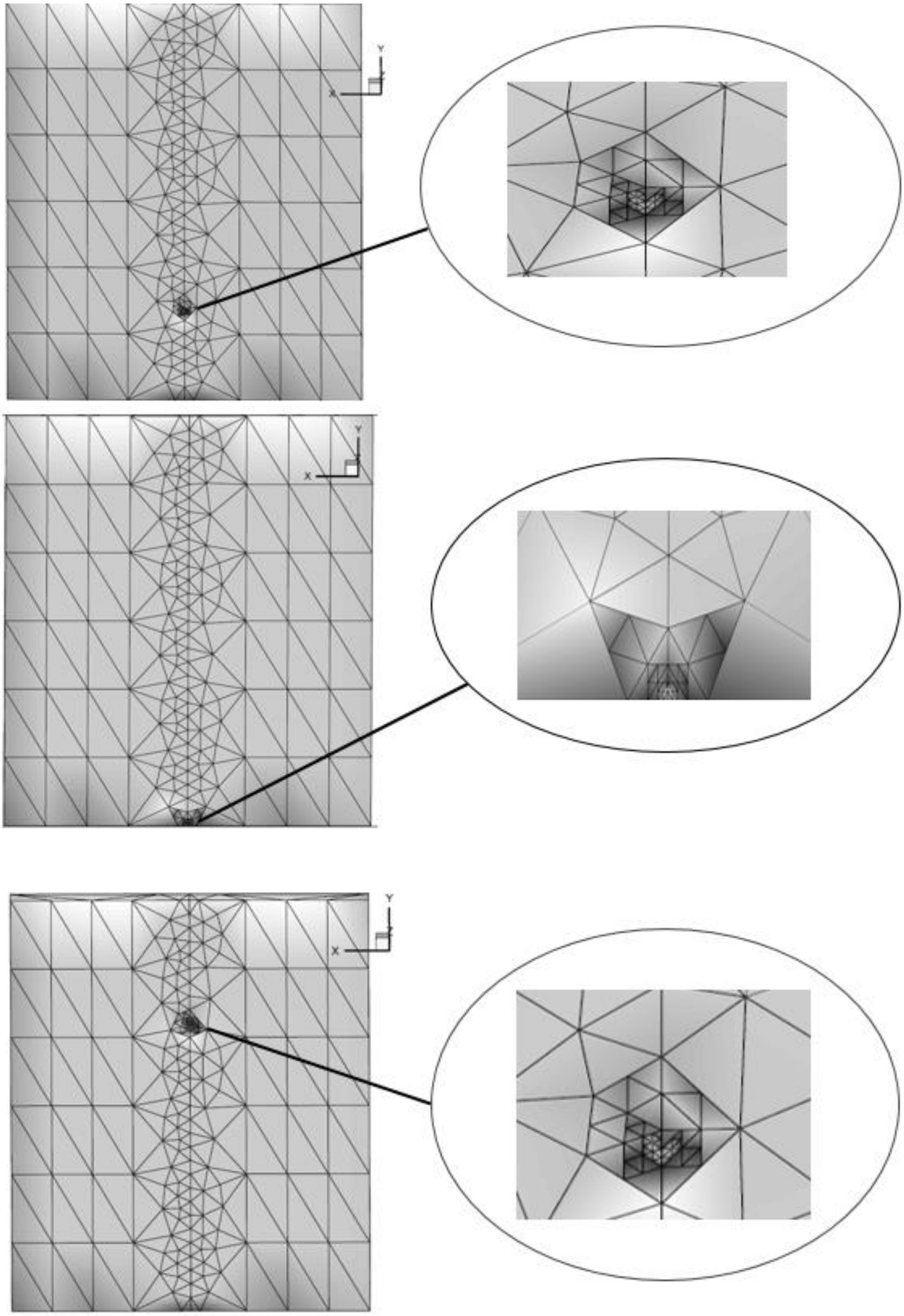


Fig. 9. Evolution of the proposed adaptive mesh model, a) T=0 S, b) T=9S, c) T=28S

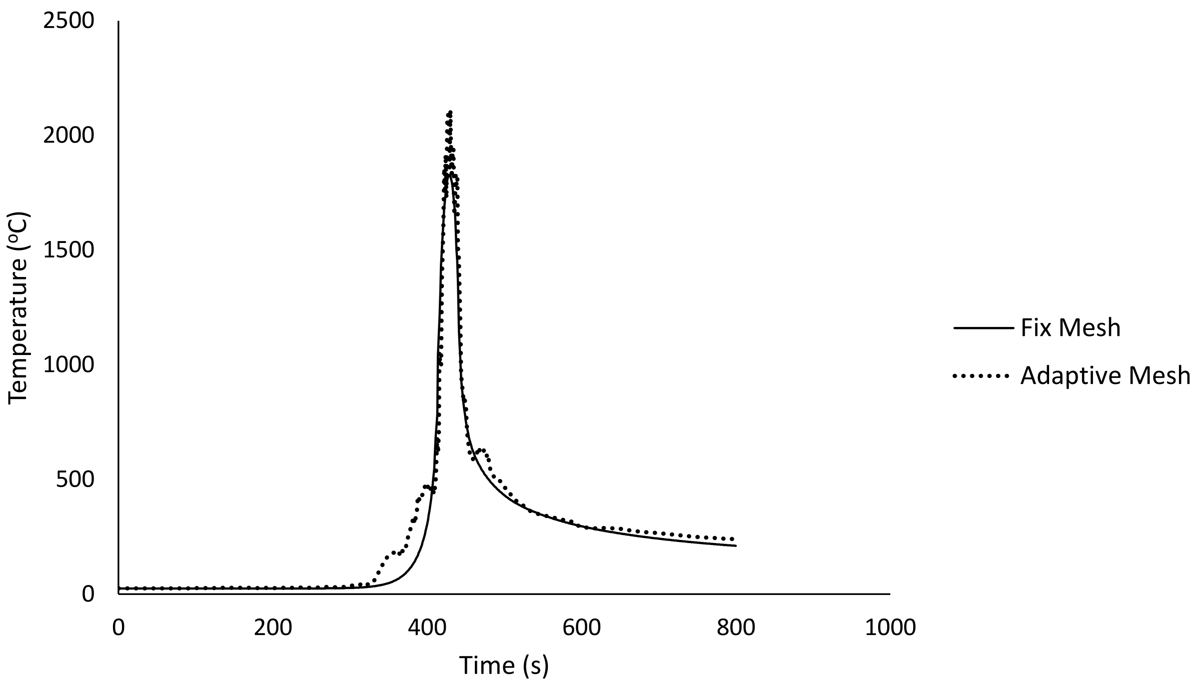


Fig. 10. Comparison of thermal cycle on weld seam by two meshing methods

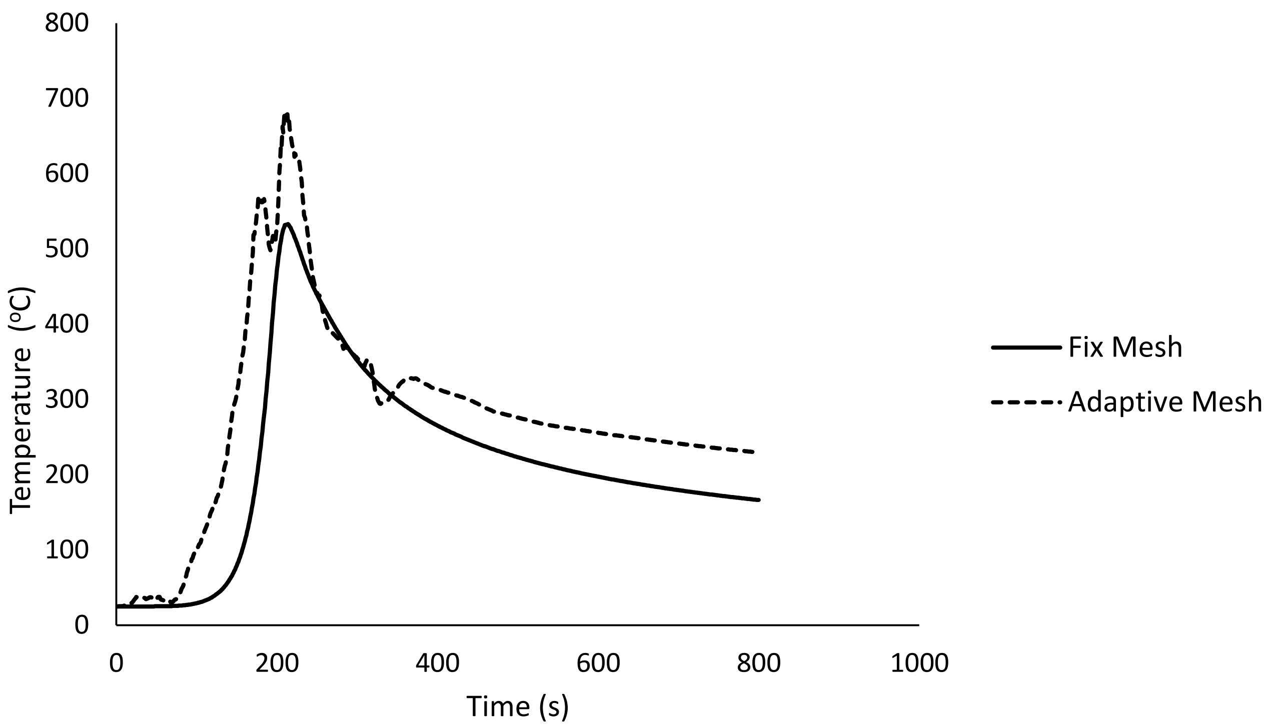


Fig. 11. Comparison of thermal cycle by two meshing methods around the seam zone

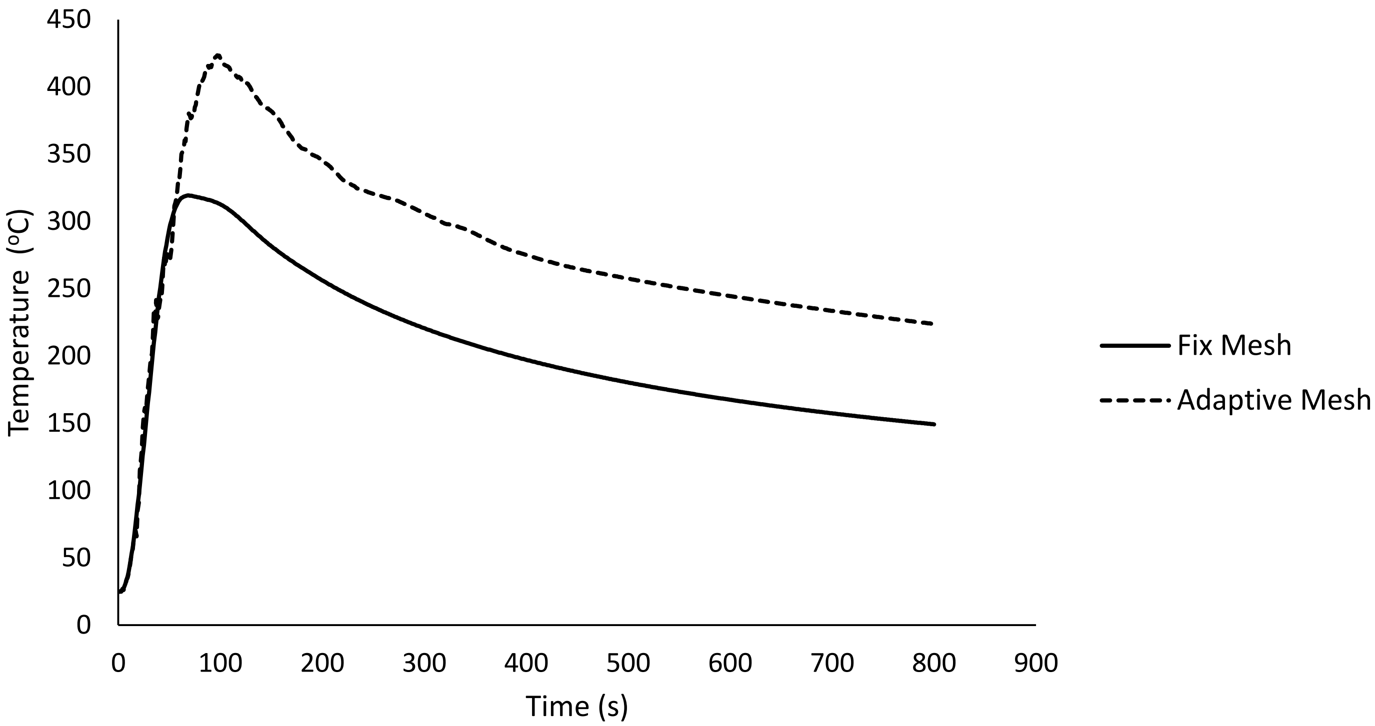


Fig. 12. Comparison of thermal cycle by two meshing methods around the sheet borders

and the seam increases, more deviation is observed between the two curves.

3. RESULTS AND DISCUSSION

3.1. Speed And Precision Of Calculation

First, a comparison is performed for analysis time necessary for ABAQUS and for finite element codes of fixed meshing and adaptive meshing methods. Table 2 gives the ratio of the results for each pair of the methods and indicates that while the fixed meshing one needs very similar time to be completed, the adaptive meshing method accelerates the calculation about 4.5 times.

In other words, according to Table 2, the speed of computation in the adaptive meshing method is much higher than the other two methods and at the same time, as seen before the precision of the computation results is completely acceptable, mainly near the weld seam.

3.2 Experimental Simulator

Welding simulator comprises a high-performance computer, an Xbox One Kinect and a manual welding holder with a real electrode, as presented in Fig. 13.

To explain the simulation procedure of welding, Table 3 gives a general overview of main parts of the simulator and their relations. In every step of calculation time, first, the POS of the hand and the electrode are measured relating to an arbitrary base frame. Then a 3D heat model is solved in real-time and provides the temperature distribution data. The computer then updates the spark, the temperature distribution, and the process sound and evaluates a novice once the operation is terminated.

In Fig. 14, the main window of the welding simulator is observed. The simulator starts welding if the electrode is positioned on a certain location of the virtual workpiece. The ambient light becomes slightly brighter at the start point in order to indicate arc light. On the main window, the presence of some buttons is planned to get the results and change the input parameters such as current, arc length, and electrode diameter.

To start welding, the user chooses the diameter of the electrode and the current according to the thickness of the workpiece (Fig. 15). the developed program permits the adjustment of arc length at the beginning of the process. To this end, an experimentally proposed value is prescribed in the control panel and the user should respect this value all along with the operation.

3.3 Evaluation Part

3.3.1 Result Window

In a result window, the user could observe a detailed

Fig. 13. Elements of the welding simulator

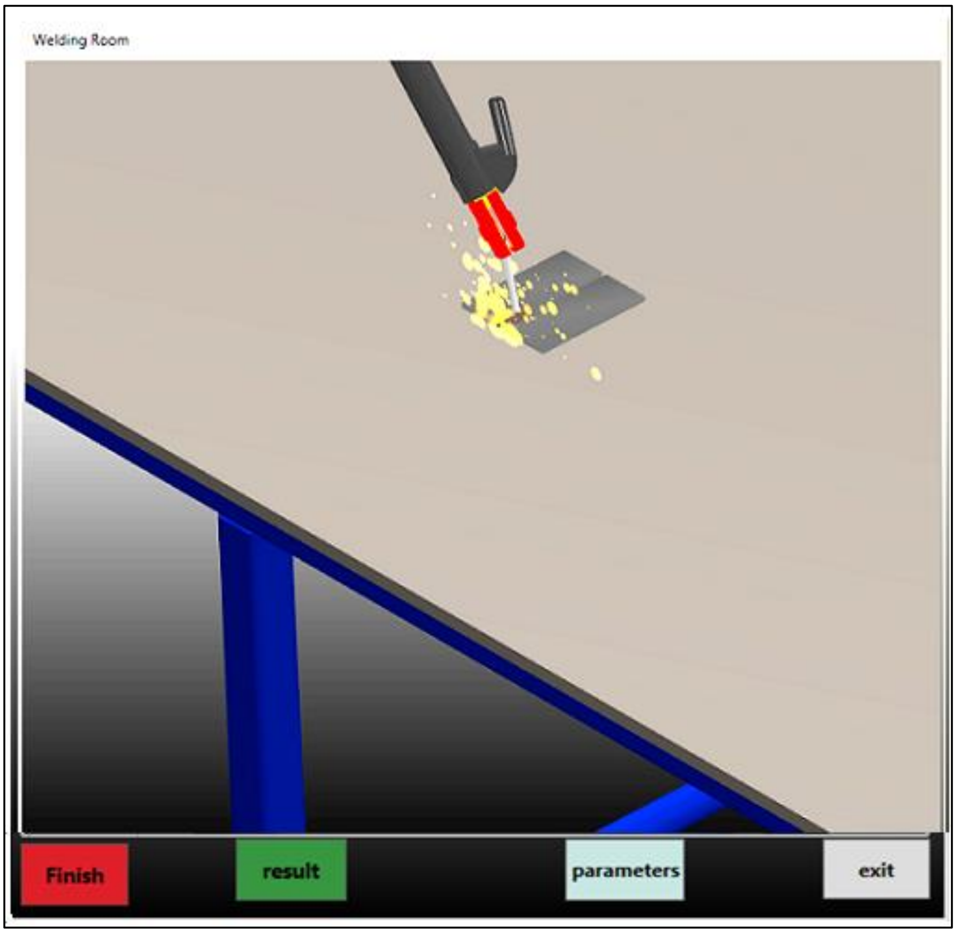
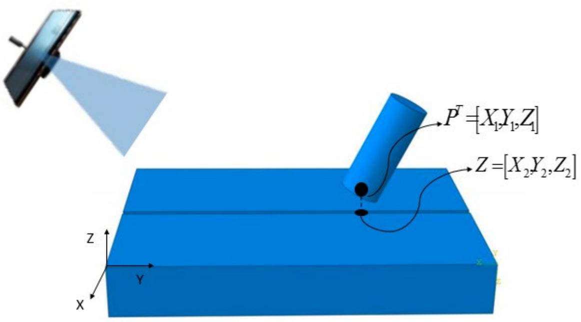


Fig. 14. Main window for the simulator

Table 2. Calculation time ratio

Parameter	lue
$\frac{\text{ABAQUS method}}{\text{fixed meshing method}}$	1.05
$\frac{\text{ABAQUS method}}{\text{adaptive meshing method}}$	4.64
$\frac{\text{fixed meshing method}}{\text{adaptive meshing method}}$	4.38

Table 3. Procedure of welding simulation

<table>
<tr><th>Real environment: Kinect tracker</th><th colspan="2">Physics engine</th><th>Virtual welding environment</th></tr>
<tr><td rowspan="5">
</td><td rowspan="5">Coordinates of the hand and electrode X1, Y1, Z1</td><td rowspan="5">3D heat analysis with proper computational speed using welding parameters</td><td>Display the heat real-time distribution</td></tr>
<tr><td>Welding spark</td></tr>
<tr><td>Change the ambient light due to the arc</td></tr>
<tr><td>Spark sound</td></tr>
<tr><td rowspan="2">The position of the electrode real-time relative to the seam</td></tr>
<tr><td rowspan="2">Measuring of the hand and the electrode coordinates relative to the base frame</td><td colspan="2" rowspan="2">Novice evaluation</td></tr>
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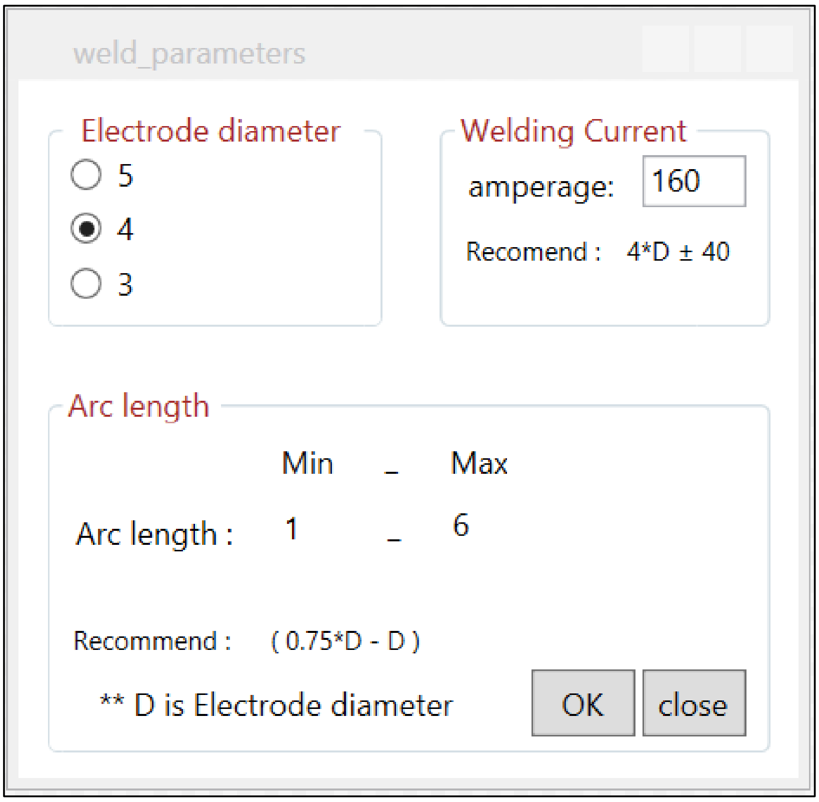

Fig. 15. Welding parameters control panel

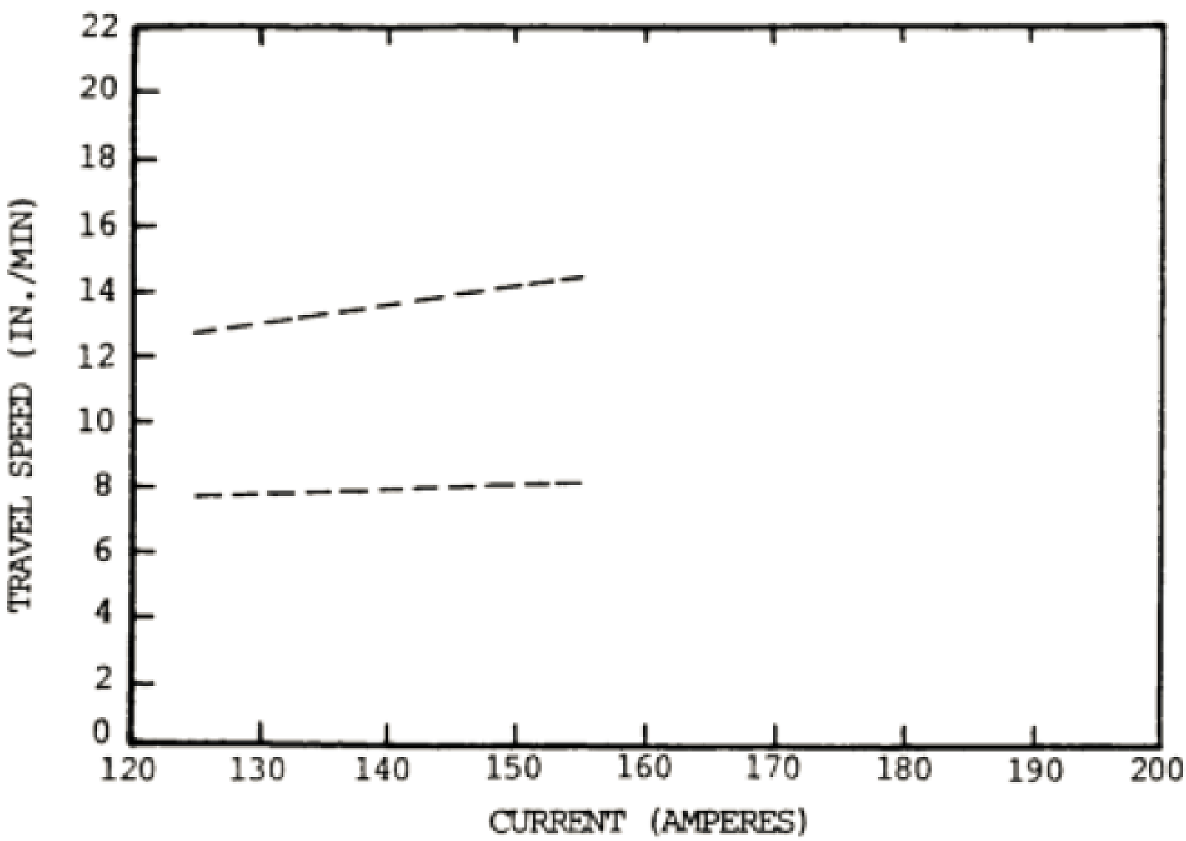

Fig. 16. Hand speed for 6013 electrode with a diameter of 1/8 in reference [25]

evaluation of performance after the welding (Fig. 17). Three different graphs are depicted; the first one shows the arc length versus the position of the electrode, the second one presents the hand speed versus the position of the electrode and the third graph gives the user's hand coordinates during operation.

Other extracted information from this window is the user's score. Based on the user's performance in respecting allowable hand speed and arc length, the user obtains a score between 0-100. Considering the importance of each of these two parameters, a variable weighting coefficient is assigned to determine the overall score.

3.3.2 User Evaluation

The user result is supposed to be visualized in one click. As mentioned before, two parameters of arc length and hand motion speed compose the final note. Other parameters such as electrode inclination angles are not considered because of the difficulties in measuring by the Kinect camera.

3.3.2.1 Welding Arc Length

The arc length has a direct influence on the weld quality and should be adjusted depending on the diameter of the electrode. The arc length is roughly estimated to be the same or a little smaller than the electrode diameter. The results of this relation achieved from some experimentations are given in Table 4.

3.3.2.2 Hand Motion Speed

As shown in Fig. 16, a convenient value for hand travel speed is expressed in terms of the type and diameter of the electrode [25]. During the welding process, the operator automatically adjusts the hand speed by visual feedback from filling the melt pool. After the operation, if the workpiece seam is completely filled, and discontinuity and lack of fusion has not occurred, the traveling speed would be acceptable. First, according to the selected current, the allowable speed limit is obtained. However, with a rise in the electrode diameter, the hand movement speed should slightly decrease.

3.3.3 Experimental Results Of The Simulator

The performance tests of the proposed simulator include 3 categories: poor observance of arc length and good observance of hand travel speed; medium observance of arc length and hand travel speed, and good observance of the hand travel speed and arc length.

In the first essay, the user does not respect a proper arc length and passes the electrode too far from the seam. So as shown in the scoreboard of Fig. 17, the arc score is very low. But since the travel speed is attentive, a good score is recorded for the second part.

The second test is carried out with a medium performance for the arc length and the travel speed. Fig. 18 shows that some discontinuities occurred during virtual welding, consequently the scores are not quite good during this test.

In the last test, the user has acquired good skills in welding, and Fig. 19 demonstrates better performances in comparison to the previous case. Here the arc length and the travel speed have similar scores. However, a lack of welding is just observed at the beginning and at the end of the seam.

3.3.4 Comparative Results For A Population Of 30 Novices

To determine the welding skill level of a novice who participates in a welding course, using a results chart to indicate the level and the progress amount is rather confusing. Therefore, a method is proposed for a statistical population of 30 novices. The members of this population have different skill levels in manual arc welding and are invited to test the simulator while their scores are recorded. The 3D graph obtained from the statistical population's scores is depicted in Fig. 20 where 3 axes show travel speed, arc length, and final score.

Participants who are situated in dark blue and blue zones, are the ones with very low skill levels and need a great effort in welding practice; i.e. the novice should be trained to control simultaneously the arc length and the motion speed.

Table 4. Experimental relation between arc length and electrode diameter

Electrode diameter (mm)	Maximum of arc length (mm)
1.6	1.6-2.4
2.4	2.4-1.8
3.2	3.2-2.4
4	4-3
4.8	4.8-3.5
6.4	6.4-4.8

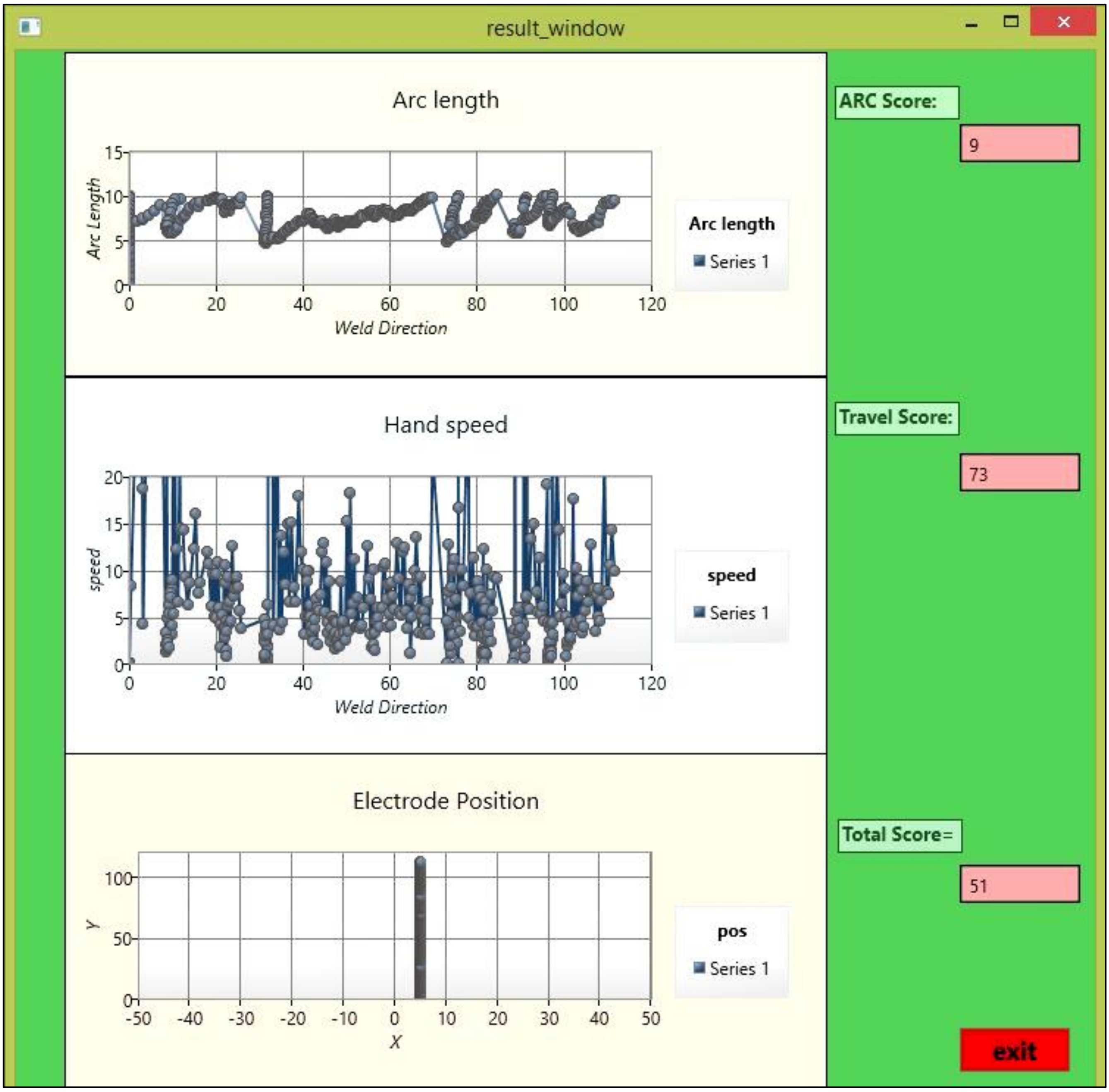

Fig. 17. Results for poor observance of arc length and good observance of hand travel speed

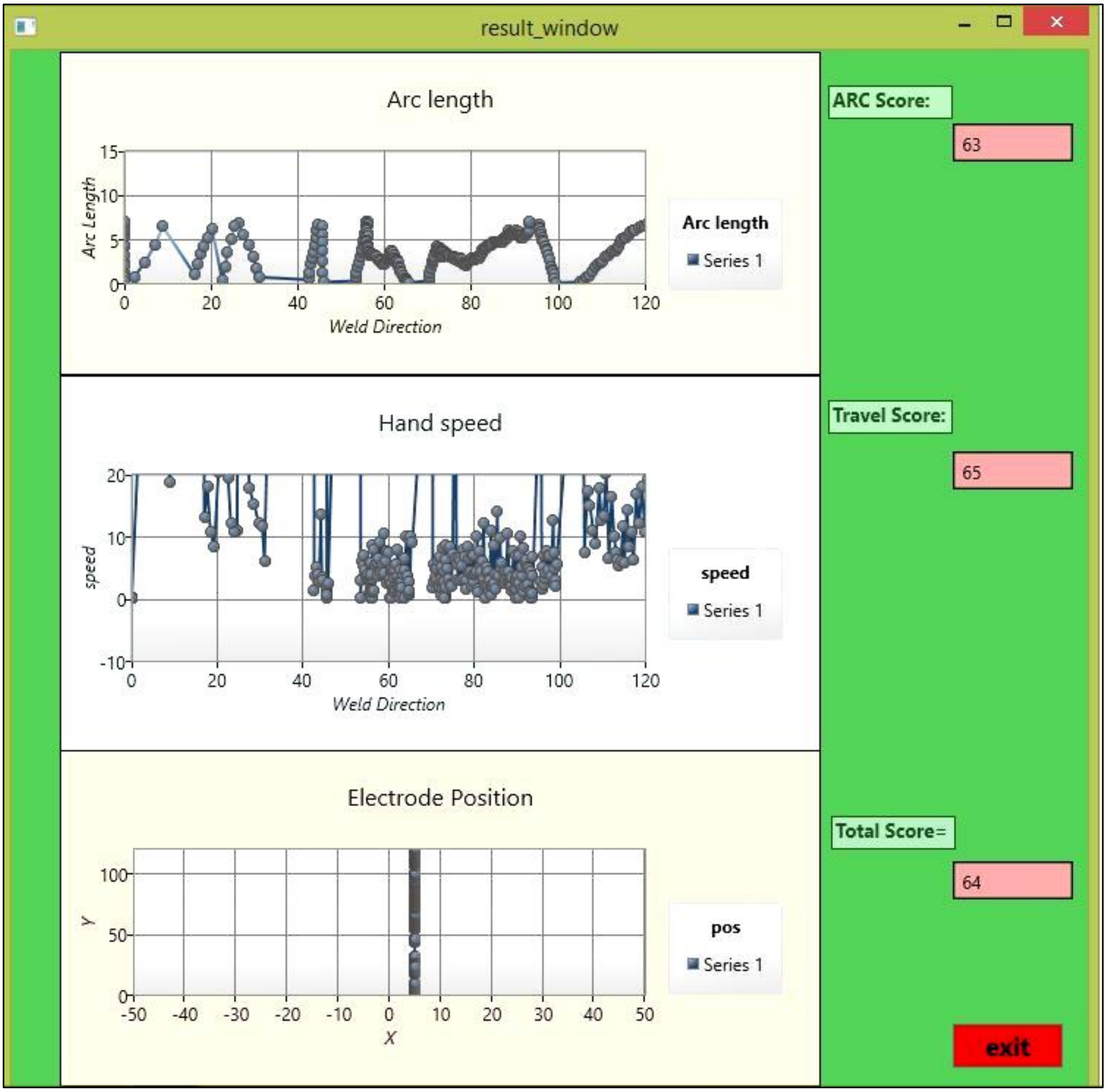

Fig. 18. Results for medium observance of arc length and hand travel speed

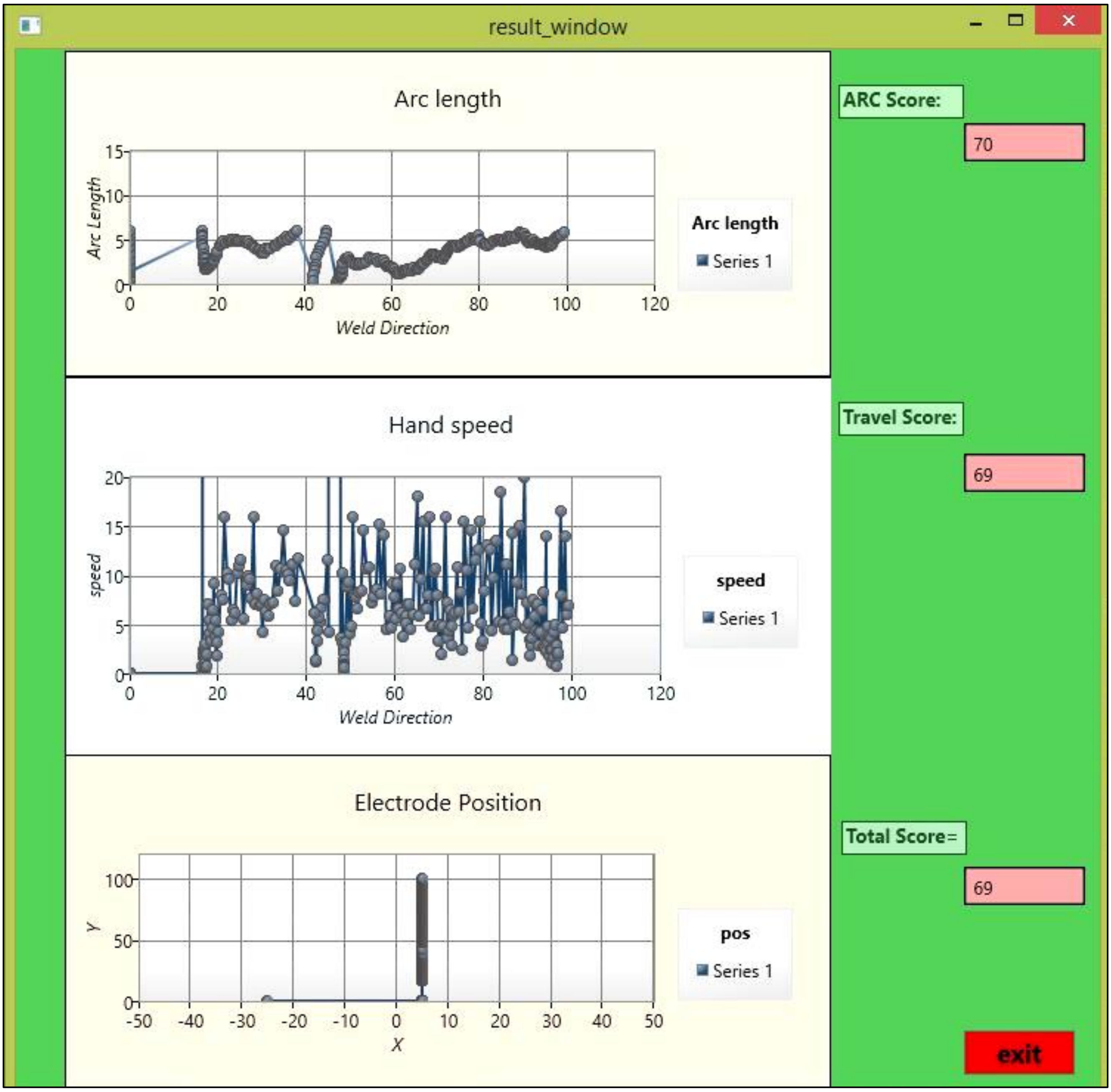

Fig. 19. Results for good observance of the hand travel speed and arc length

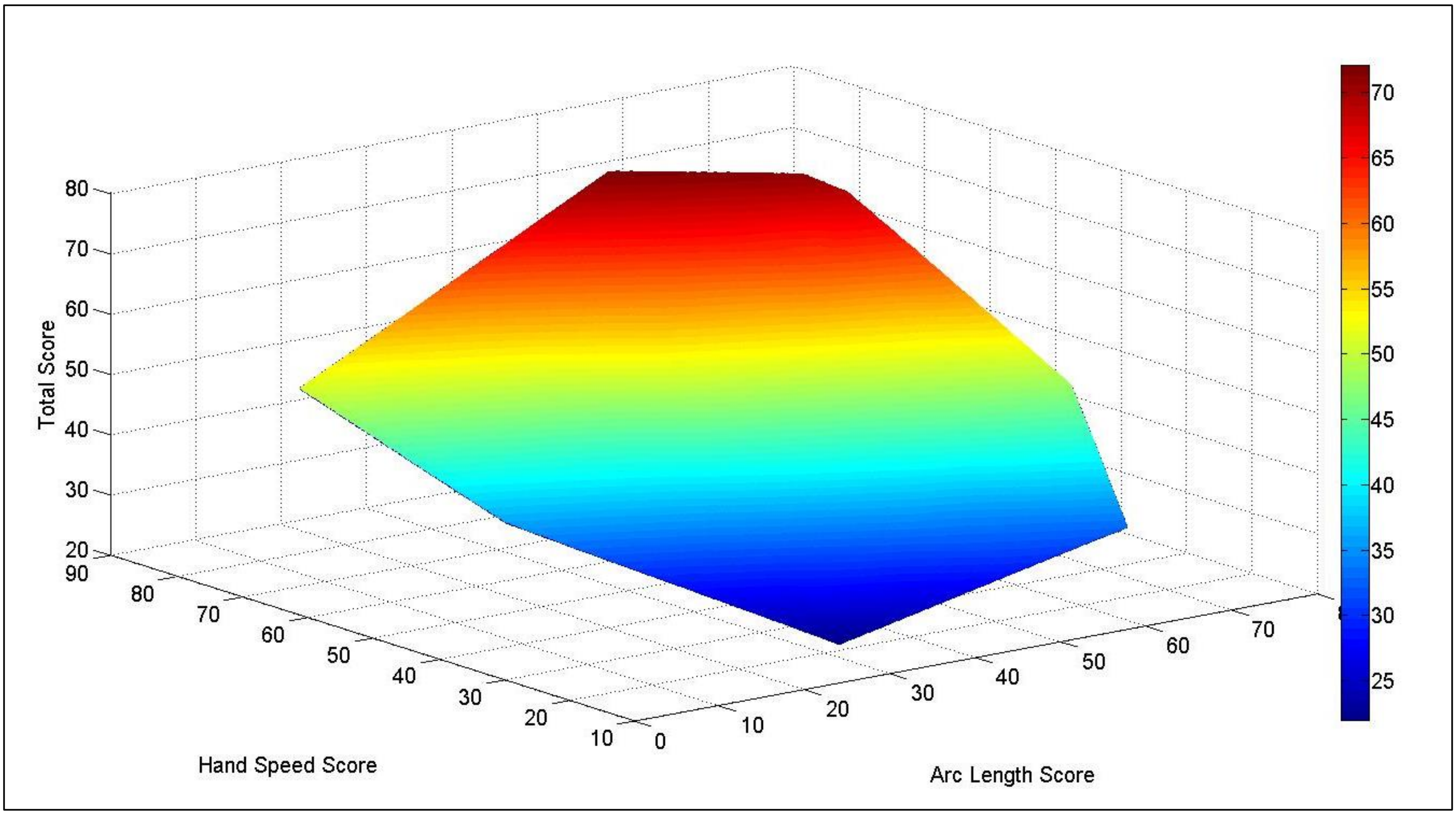

Fig. 20. Comparison of the overall scores obtained for 30 essays of the simulator

This range corresponds to the novices with poor levels who need more training hours to achieve a high skill level.

The yellow zone concerns the novices with an average score which means that they acquired a good scientific level but to improve their practical level, they need more training in controlling motion speed and arc length. Finally, the red zone demonstrates good results for novice and he could be considered as a skillful welder in terms of respecting two important parameters of arc length and hand travel speed.

4. CONCLUSIONS

a. In this article a simulator of arc welding is developed by using two finite element models, with fixed and adaptive meshing. Fixed meshing gives very good results and provides the same precision as ABAQUS software. However, the calculation is too slow by this method, while the adaptive method goes very fast and satisfies the real-time characteristics of the simulator.

b. For tracking the hand and the electrode, a Kinect Xbox is used and a distance of 4.5 m is covered with no limitation on the user's motion.

c. A novice of welder could take enough time to learn manual arc welding without any extra cost or danger.

d. One of the positive features of the simulator is self-learning, i.e. the user will get an effort to improve his skills by getting his score and viewing the details of performance on the results page.

e. While the novice is a welder, a trainer could give necessary advice and the novice will instantaneously improve the welding skills. On the other hand, the weak points in real welding are not easily improved because of the light and the sparks of the process, so the skills could be evaluated only by the weld bead.

f. The simulator provides a good training ability to control the arc geometry and the motion speed.

Nomenclature

R	Heat flux rate,
T	Temperature,
Q	Heat generation rate, J
c	Heat capacity,
t	Time, s
K	Heat conductivity coefficient,
N	Shape matrix
C	Capacity Matrix
H	Heat transfer coefficient,
V	Voltage
I	Current
ρ	Density,
conv	convection
conj	conduction
rad	radiation

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