Reduced order model for evaluating the temperature gradients of the surfacing weld process

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Abstract: Surfacing weld represents the deposition of a filler material on the surfaces or edges of a base metal. The objective of the process is to improve the mechanical characteristics of metallic structures that are subjected to cyclic loads. Heat transfer occurs at the interface between the welded beads and the base metal. Thus, the structural performances of the final product are limited. In this regard, the evaluation of the temperature distribution by means of simulation tools can provide essential information to the designers of such structures. The present paper proposes a new approach for the estimation of the thermal gradients that occur during the welding process. In the first stage, a black box system is developed with the support of experimental data. A simulation approach that is based on the Finite Element Method is proposed for the transient analysis of the heat transfer. The conductance and capacitance of the model are defined based on the parameters of the "Black box" system.

Keywords: Welding, Heat Transfer, Black Box, Simulation.

Model cu parametru redus pentru evaluarea gradienţilor de temperatură a procedeului de încărcare prin sudare

Rezumat: Încărcarea prin sudare reprezintă operaţia prin care un material de adaos este depus pe un material de bază. Scopul procesului este acela de îmbunătăţire a caracteristicilor mecanice a reperelor care sunt solicitate ciclic. Transferul de căldură care apare la interfaţa dintre straturile depuse şi materialul de bază limitează performanţele produsului finit. În acest sens, evaluarea distribuţiei de temperatură cu ajutorul instrumentelor de simulare poate oferi informaţii esenţiale proiectanţilor unor astfel de structuri. Lucrarea de faţă propune o nouă abordare pentru estimarea gradienţilor termici care apar în urma procesului de încărcare prin sudare. În prima fază, un sistem de tip “black box” este dezvoltat având ca referinţă valori experimentale. O abordare de simulare bazată pe Metoda Elementelor Finite este propusă pentru analiza transferului de căldură în regim tranzitoriu a procesului. Conductanţa şi capacitanţa modelului sunt definite pe baza parametrilor sistemului “black box”.

Cuvinte cheie: Sudare, Transfer de Căldură, Black Box, Simulare.

1. Introduction

Surfacing weld represents a single or multiple pass deposition of a hard, wear-resistant layer of filler material to the surfaces or edges of a base metal Surfacing weld (Garbade & Dhokey, 2021). The aim of the process is to extend the life time of mechanical parts that operate in severe conditions (Singh et al., 2022). Gas Metal Arc Welding (GMAW) represents one of the most common surfacing weld procedures (Botez et al., 2011). Due to this fact, the complexity of the welding setup and its operational costs are kept at the lowest possible figures (Cheng et al., 2021).

However, one major disadvantage of the process is the existence of a Heat Affected Zone (HAZ) in the proximity of the welded joint (Mičian et al., 2020). As a consequence, the mechanical and structural properties of the filler material are sensitive to the heat transfer of the welding procedure (Hussin & Lah, 2020).

First order systems are commonly employed in the design of control systems to model the dynamics of the plant (Junfeng & Chunlong, 2012). They describe the relationship between the input and output variables by means of a first order differential equation. The system gain (or how much the output changes for a given input) and time constant (or how quickly the system responds to changes in the input) are taken into consideration. Dead time is included as a constant time shift to capture the delay that occurs between the input and the response of the system.

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The temperature distribution that occurs in surface weld processes is a complex and dynamic phenomenon that is influenced by several factors, such as the welding parameters, material characteristics and the environmental conditions (Arora et al., 2019). Thus, an accurate representation of the process requires an in-depth description of the heat transfer. Typical approaches are based on Finite Element Method (FEM) coupled analysis (Mahiskar et al., 2014) or Computational Fluid Dynamics (CFD) models (Schnick et al., 2011).

Both FEM and CFD models represent numerical methods that employ a mesh to discretize the physical domain of the welding process and solve the governing equations of heat transfer and fluid flow. These models can provide a detailed representation of the temperature distribution and other important variables, such as residual stresses and distortion.

Even so, First Order or First Order Plus Dead Time (FOPDT) systems can be employed for the simplified modeling of the temperature distribution in surface weld processes. This objective can be completed by combining a FOPDT system, FEM thermal analysis and experimental procedures.

In this regard, a FOPDT model of the surface weld process can be developed based on experimental data or historical records (Photoon & Wichakool, 2015). The aim of the model is to describe the relationship between the process input (i.e. the welding current) and the output (the temperature in a specific location) in terms of the system gain, time constant and dead time.

On the other hand, FEM thermal analysis takes into account the material properties, heat input and cooling rates. From this perspective, the FOPDT model can be used to provide boundary conditions for the heat transfer simulation (Park et al., 2020).

Furthermore, experimental procedures can validate both the FOPDT and the FEM model. These experiments capture the temperature distribution in the welded joint with the support of thermocouples or infrared cameras (Rose et al., 2010).

Thus, by combining different experimental and simulation procedures, an accurate description of heat transfer which occurs in welding processes can be obtained.

Several papers deal with the simulation of the thermal gradients of the surface weld processes.

For instance, the work published by (Roshyara et al., 2011) describes an analytical model for the approximation of temperature fields in arc welding. On the other hand, the research carried out in (Moreira et al., 2007) captures the temperature curves of weld beads by means of an experimental approach. Furthermore, the papers (Arsić et al., 2020; Sachajdak et al., 2018) describe simulation models that are based on Computational Fluid Dynamics (CFD) or the Finite Element Method (FEM).

Opposed to the existing literature, the present paper proposes a new approach for the transient simulation of the heat transfer that occurs in the surfacing weld process. The methodology is based on black box and FEM modeling techniques.

In the first stage, a batch of experimental samples is decided. Each specimen is subjected to bead welding. Different welding parameters are considered for completing the study. Temperature acquisition is carried out in a location that is found outside the welded joint to limit the side effects of electromagnetic interference.

The experimental values are processed in a numeric computing environment. A black box model is developed with the support of system identification procedures. The numerator and denominator coefficients of the resulting transfer function are evaluated for each studied specimen.

In the next stage, FEM simulations are employed by considering an ideal heat transfer environment. Constraints are applied to the conductance and capacitance of the model. The values used are mapped to the behavior of the black box system. Thus, accurate simulation results can be achieved without extended knowledge requirements.

2. Materials and methods

2.1. The proposed approach

The proposed approach consists of two layers of abstraction: the experimental and the simulation layer (Figure 1).

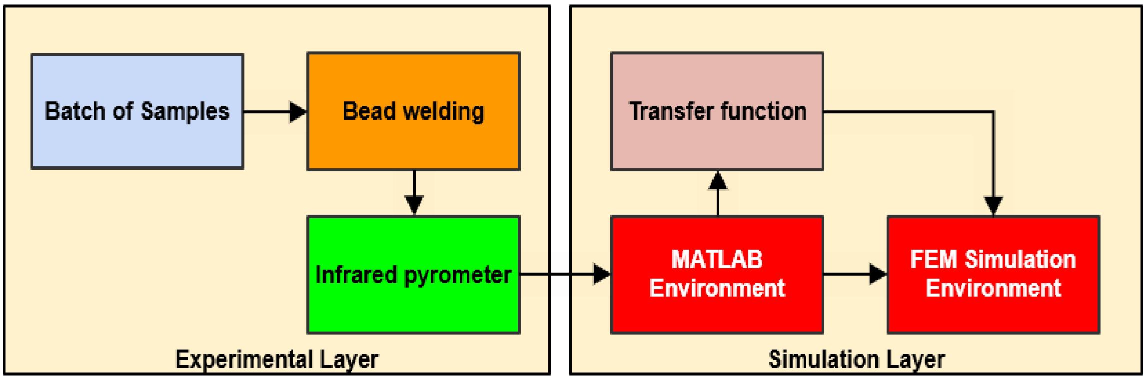

Figure 1. A schematic representation of the proposed approach

A brief description of the constitutive layers is carried out below:

• **The experimental layer:** An experimental assessment is carried out for evaluating the temperature curves of the stringer bead welding process. A batch of 5 samples that are manufactured from S235JR steel are employed for this purpose. Each work piece has a thickness of 10 mm and a surface area of 20000 mm^2. The same current intensity is used for all specimens, but different gas flow rates. These process parameters are decided for extending the simulation capabilities of the model. A location that is found outside the welded joint is considered for thermal acquisition. An infrared pyrometer is employed for capturing the temperature gradients.

• **The simulation layer:** The start and end time of the welding and temperature acquisition processes are synchronized. Afterwards, the resulting input and output variables are exported to the MATLAB numeric computing environment. Noise filtering techniques are employed for removing the noisy acquisition data. The relevant signal statistics are processed for each studied sample. Graph observations are carried out for adopting an optimal system identification methodology. The numerator and denominator constants of the resulting transfer function are mapped to the welding process parameters. A FEM simulation model is developed in an ideal environment. Thermal conductance and capacitance elements are employed to constrain the dynamic behavior of the system. Their parameters are decided based on the constants of the black box model. Thus, the temperature gradients of the surfacing weld process can be processed in virtually any location of the base metal.

2.2. The experimental layer

The experimental setup comprises a MIG-MAG robotics welding cell that includes the standard equipment for gas metal arc welding processes: a robotic arm, the welding power source, the wire feeder, the welding torch, a shielding gas supply and a process control system. A non-contact temperature acquisition system is employed for capturing the thermal gradients. Referring to Figure 2, the base metal (1) is secured in place by a fixture (2). An industrial robot (3) that is equipped with a welding torch (4) carries out the bead welding process. During the experiments, an infrared pyrometer (5) continuously acquires the temperatures from a location that is found outside the welded joint (6). The values are stored on a PC (7) for further processing.

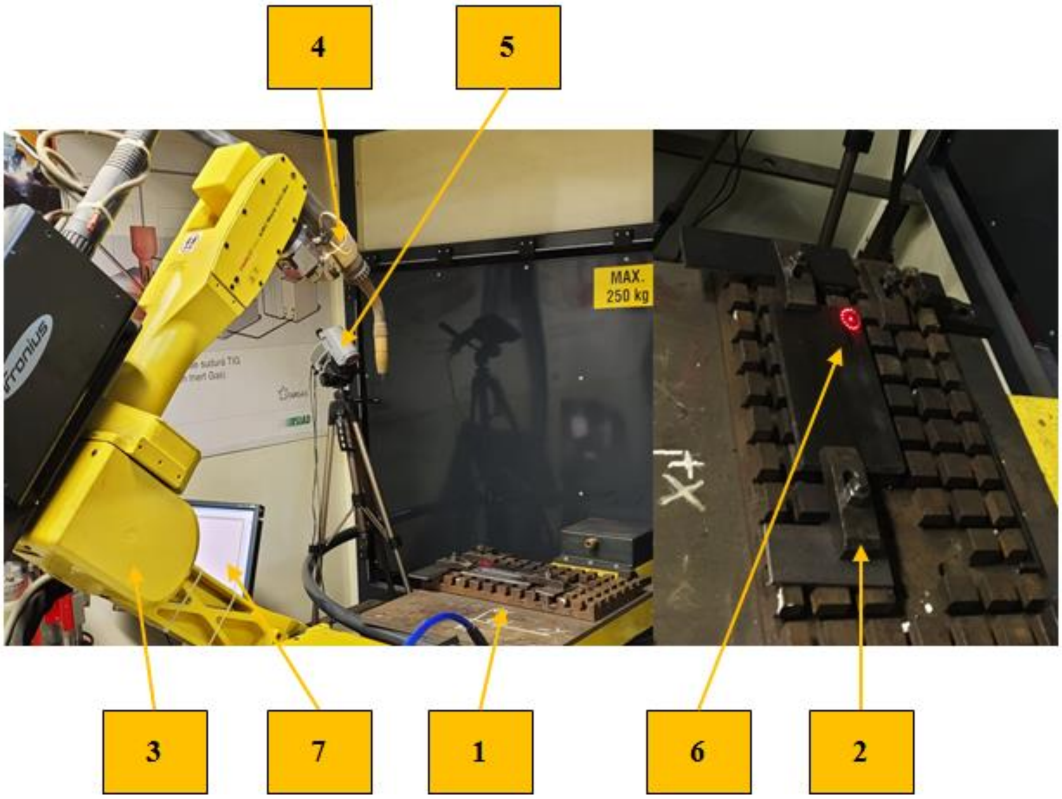

Figure 2. Details regarding the experimental setup

Table 1 depicts the welding parameters that are employed for the studied batch of samples.

Table 1. Welding parameters employed in the study

Number of samples	Welding current (A)	Shielding gas flow rate (l/min)	Voltage (V)	Wire feed speed (m/min)	Welding speed (cm/min)
5	190	10 to 24	18.9	4.7	45

2.3. The simulation layer

The simulation layer comprises two distinct environments:

• **The MATLAB environment:** employed for processing the experimental data by using preprocessing, cleaning and plotting techniques. The relationship between the input and the output of the process is further used for deriving an s-domain transfer function. This stage is completed by employing Black Box modeling procedures (Sima et al., 2017).

• **The FEM simulation environment:** employed for developing an ideal representation of the heat transfer that occurs in the welding process. The unrealistic behavior of the conductance and capacitance of the model is overcome by mapping the simulation parameters to the variables of the Black Box model.

Figure 3 depicts a schematic representation of the interactions that occur in the two environments.

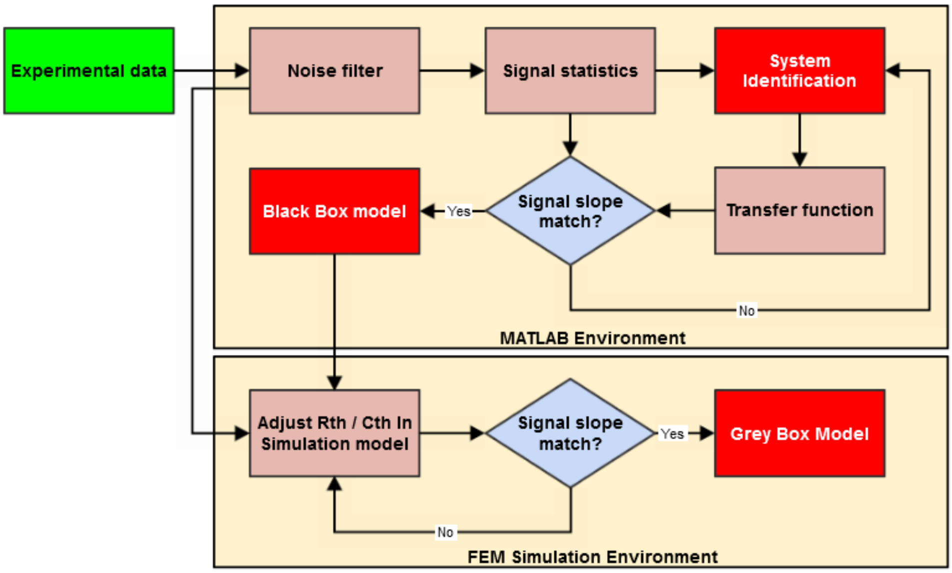

Figure 3. A schematic representation of the proposed approach

The experimental data is transferred to the MATLAB environment for further processing. In the first stage, signal filtering and smoothing techniques are employed for removing the acquisition noise. The relevant signal statistics are derived for each studied sample. Afterwards, the transient response of the process is evaluated based on the observations from the graph. System identification methodologies are used for deriving the frequency domain transfer function of the process. Multiple model structures are tested until the step response of the system matches the initial signal statistics. The resulting Black box approach has the ability to recreate the thermal behavior of the experimental temperature curves.

In the next stage, a transient thermal analysis simulation model is developed. A 3D representation of the solid domain is completed for the base metal and welded joint. The equation that governs FEM thermal analysis is depicted in (Feng et al., 2020):

$$[C]\{\dot{T}\}+[K]\{T\}=\{Q^a\} \tag{1}$$

Where: C represents the specific heat matrix, K the conductivity matrix, T the vector of nodal temperatures and Q^a the applied heat flow vector.

Equation 1 resembles a first order system. In this regard, the temperature gain and steady-state behavior are modeled explicitly by the thermal conductivity. On the other hand, the time constant of the process is governed by the density and specific heat of the material.

Thermal contact conductance and capacitance can be employed to adjust the dynamic behavior of the heat transfer process. From this perspective, the heat flux that occurs between the welded joint and base metal boundaries can be constrained by employing (Kumar et al., 2021):

$$q = R_{th} \cdot (T_i - T_j) \tag{2}$$

Where: q represents the thermal flux, R_{th} the thermal contact conductance and $T_{i,j}$ the temperatures at the contacting nodes.

The additional capacitance (C_{th}) of the solid domain can be included by employing a 0D thermal mass element. Its behavior is governed by the specific heat matrix (Rincon-Tabares et al., 2022).

$$[C_e^t] = [C_{th}] \tag{3}$$

Where: C_{th} represents the lumped capacitance of the element.

The K_c and C_{th} variables from equations (2) and (3) can be mapped to the variables of the Black Box model for generalizing the behavior of the system for any given input. Thus, a reduced order model is achieved.

3. Results and discussions

3.1. Signal processing

Figure 4 depicts the experimental temperature curves for the 5 specimens (S1 to S5), for the different gas flow rate (V_g) regimes.

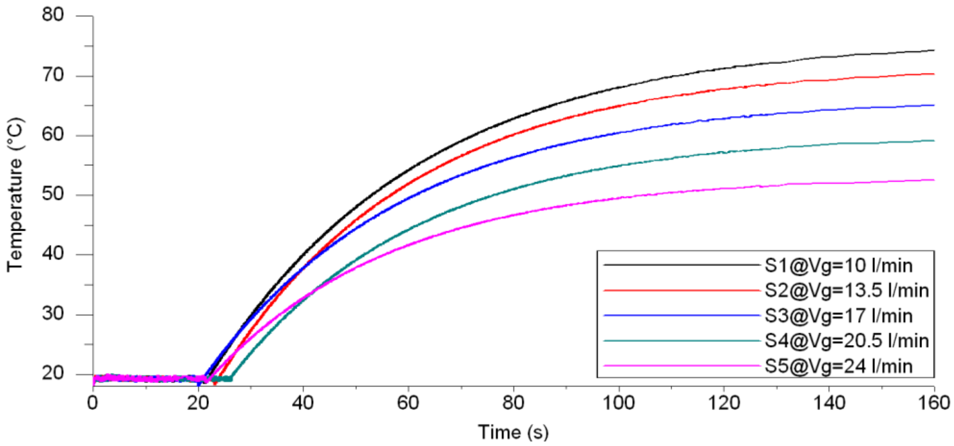

Figure 4. Experimental temperature curves for different gas flow rates

3.2. Signal statistics

The signal statistics derived for all specimens are depicted in Table 2.

Table 2. Welding parameters employed in the study

Specimen number	Maximum Temperature	Minimum Temperature	Peak to Peak	Mean
1	74.3°C	18.13°C	56.2°C	43.9°C
2	70.29°C	18.13°C	52.16°C	42°C
3	65.14°C	18.08°C	47°C	40.4°C
4	59.12°C	18.14°C	40.9°C	36.5°C
5	52.4°C	18°C	34.4°C	34.8°C

3.3. System identification

The behavior of the system matches the description of a First Order Plus Dead Time (FOPT) one, given the start slope of the curve, the process time delay and the steady-state value (Tapák & Huba, 2016):

$$\frac{Ke^{-\theta s}}{\tau s+1} \quad (4)$$

Where: K represents the temperature gain, τ the process time constant and θ the process dead time.

The curve area method proposed by Nishikawa (Nishikawa, 2007) is employed to determine the values of the constants from expression 1. Figure 5 emphasizes the locations of the two areas (A_0 and A_1) for sample number 1.

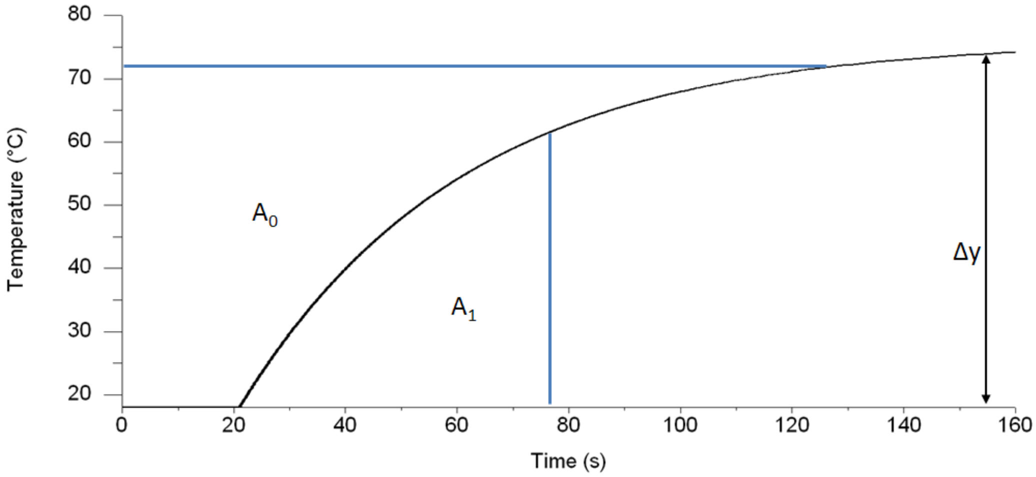

Figure 5. Experimental temperature curves for different gas flow rates

The relationships used are (Nishikawa, 2007):

$$A_0 = \int_0^{\infty} (\Delta y(\infty) - \Delta y(t))dt \tag{5}$$

$$A_1 = \int_0^{t_0} (\Delta y(t))dt \therefore t_0 = \frac{A_0}{\Delta y(\infty)} \tag{6}$$

Thus, the parameters of the first order system can be calculated based on:

$$\tau = \frac{A_1}{0.368\Delta y(\infty)} \tag{7}$$

$$\theta = t_0 - \tau \tag{8}$$

The accuracy of the model is verified by using the Mean Absolute Percent Error (MAPE) (Stoicuta & Mandrescu, 2012):

$$M = \frac{1}{n}\sum_{t-1}^{n}\left|\frac{A_t - P_t}{A_t}\right| \cdot 100 \tag{9}$$

Where A_t represents the current value, P_t the predicted value and n is the number of specimens.

Table 3 depicts the temperature gain, time constant, process delay and MAPE for each studied sample.

Table 3. Welding parameters employed in the study

Sample number	k	θ	τ	MAPE
1	57.5	21.133	37	0.45%
2	53.2	23.1	32.8	0.46%
3	48	20.1	27.5	0.51%
4	41.8	25.1	25.9	0.39%
5	34.9	21.1	24.5	0.32%

3.4. Transfer function

A generalized expression of the transfer function depicted in Equation 4 can be achieved by matching the numerator and denominator constants with the variable gas flow rate.

Figure 6 depicts the relationship between the gas flow rate and the temperature gain of the process.

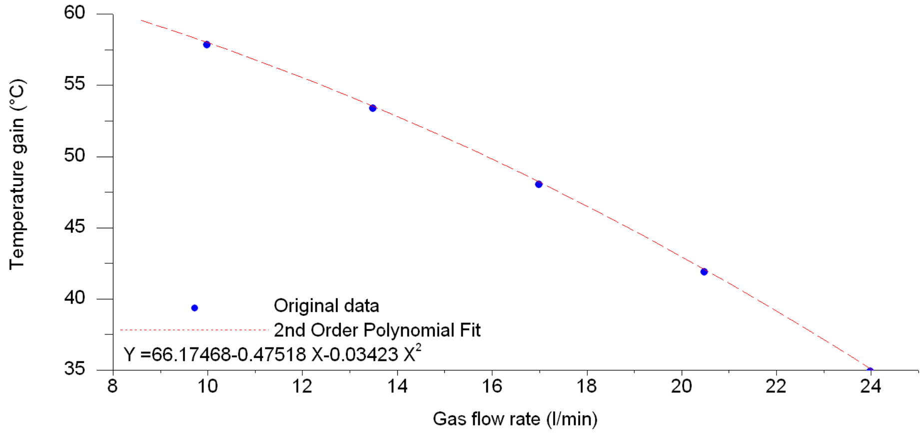

Figure 6. Experimental temperature curves for different gas flow rates

The slope of the curve matches a 2nd order polynomial expression:

$$y = 66.17468 - 0.47518 \cdot x - 0.03432 \cdot x^2 \quad (10)$$

Where: y represents the temperature gain and x the gas flow rate.

A similar slope can be noticed for the relationship between the gas flow rate and the time constant of the process in Figure 7.

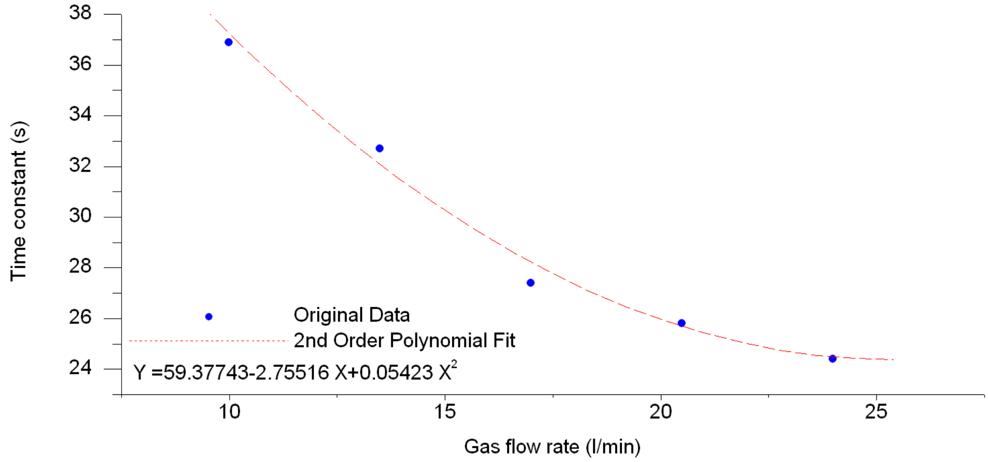

Figure 7. Experimental temperature curves for different gas flow rates

In this case, the expression of the 2nd order polynomial is:

$$y = 59.37743 - 2.75516 \cdot x + 0.05423 \cdot x^2 \quad (11)$$

Where: y represents the time constant and x the gas flow rate.

3.5. FEM Simulation model

A FEM simulation model is developed by employing ANSYS Workbench software. The following settings are employed:

- Analysis type: Transient Thermal

- Total simulation time: 160 seconds
  - 20 seconds: for the welding cycle
  - 140 seconds for the cooling cycle
- Heat transfer conditions
  - Conduction: occurs at the solid domain level due to the thermal characteristics of the material.
  - Prescribed body temperature: employed for the individual sections of the welded joint. The values are derived in the experimental layer.
  - Convection: employed for the exterior surfaces of the model. The film coefficient is derived from (Jaidi & Dutta, 2004)

A 3D tetrahedral mesh is used to represent the solid domain in Figure 8.

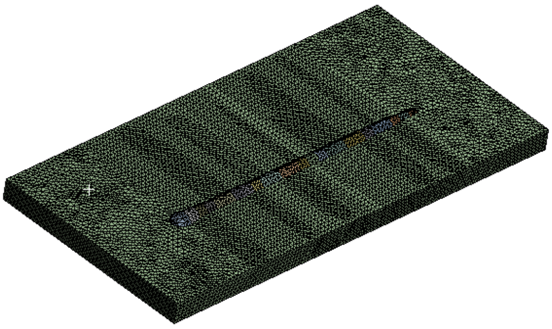

Figure 8. 3D Mesh of the solid domain

To this end, the simulation model considers an ideal interaction between the welded joint and the base metal. On the other hand, the temperature gain and time constant of the process are constrained only by the thermal conductivity, density and specific heat of the material.

Figure 9 depicts the experimental vs. simulation temperature curve for sample number 1.

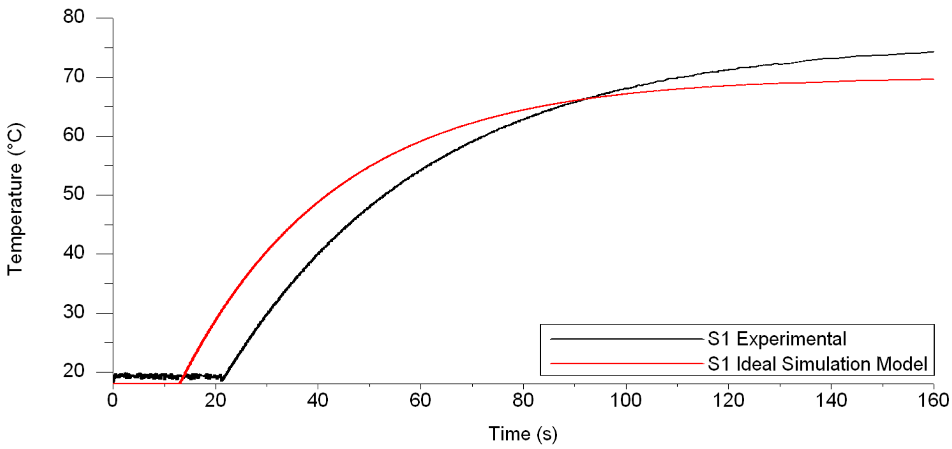

Figure 9. Experimental and simulation temperature curves for sample 1

A slight difference can be noticed between the two curves. Their statistics are depicted in Table 4.

Table 4. Signal statistics derived for the experimental and simulation curves

Derived from	Maximum Temperature	Minimum Temperature	Peak to Peak	Mean
Experimental	74.3°C	18.13°C	56.2°C	43.9°C
Simulation	69.6°C	18.0°C	51.6°C	47.2°C

Thermal interface conductance is employed at the junction between the welded joint and the base metal to overcome such issues. Figure 10 depicts the results of a parametric study that was completed for identifying the optimal conductance value.

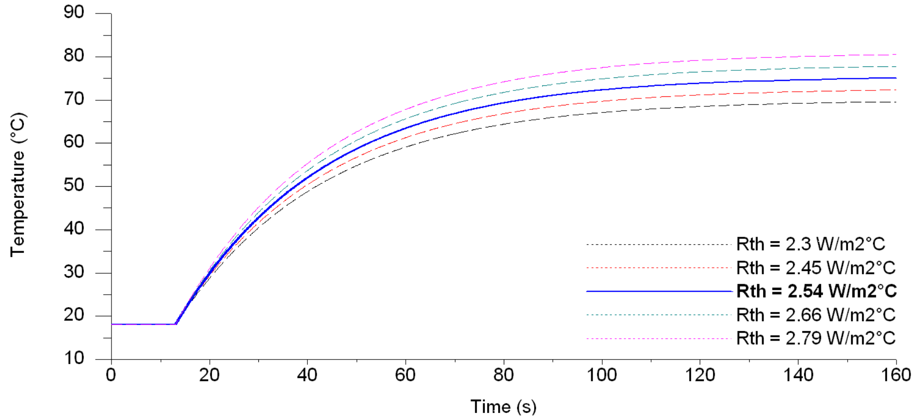

Figure 10. Interface conductance parametric study, temperature gain match = 2.54W/m^2°C

The same approach was employed for identifying the capacitance of the model in Figure 11.

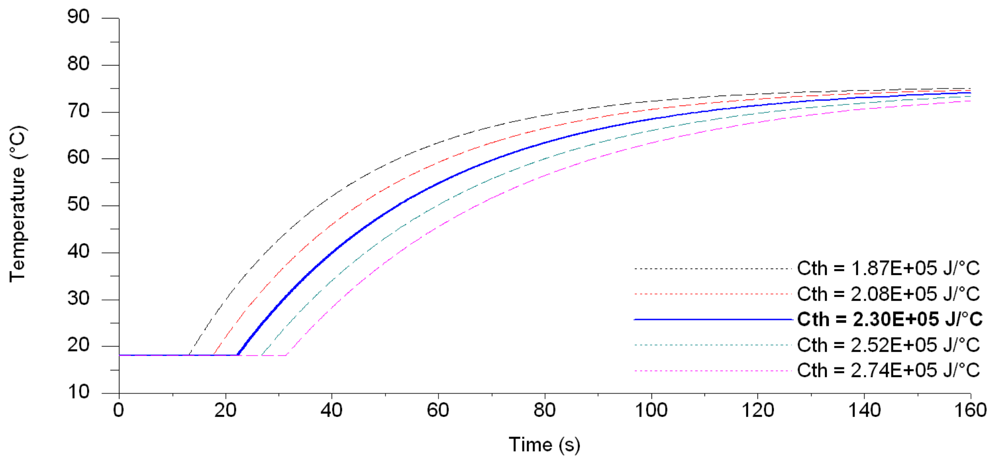

Figure 11. Capacitance parametric study, time constant match = 2.30E+05 J/°C

Table 5 depicts the identified values for all studied samples side by side with the temperature gain and time constant derived in the previous stage.

Table 5. Conductance, capacitance, temperature gain and time constants for all studied samples

Specimen number	C_{th}	R_{th}	k	τ
1	2.54	2.30E+05	57.5	37
2	2.39	2.04E+05	53.2	32.8
3	2.15	1.71E+05	48	27.5
4	1.89	1.61E+05	41.8	25.9
5	1.57	1.53E+05	34.9	24.5

The relationship between the temperature gain and the interface conductance considered for each simple is depicted in Figure 12.

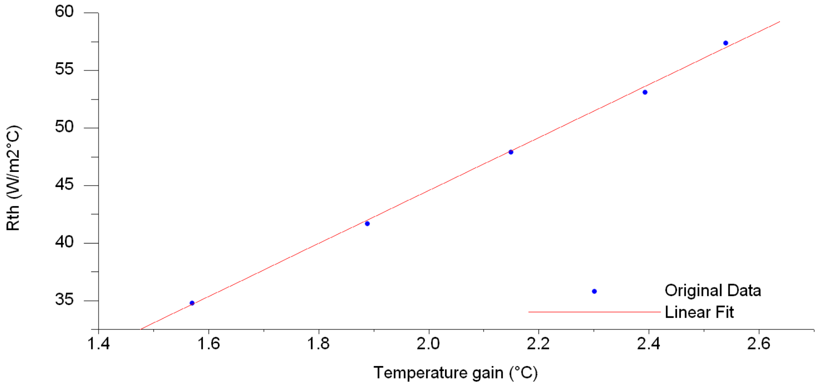

Figure 12. The relationship between the temperature gain and the conductance of the model

The relationship between the time constant and the capacitance considered for each sample is depicted in Figure 13.

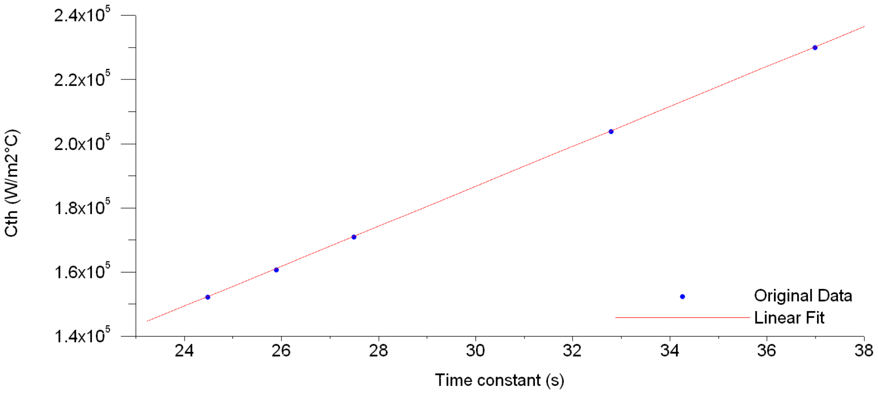

Figure 13. The relationship between the time constant and the capacitance of the model

A linear mapping can be noticed between the two sets of constants. Thus, generalization of the methodology can be achieved for different process parameters.

Figure 14 represents the practical use of the simulation model.

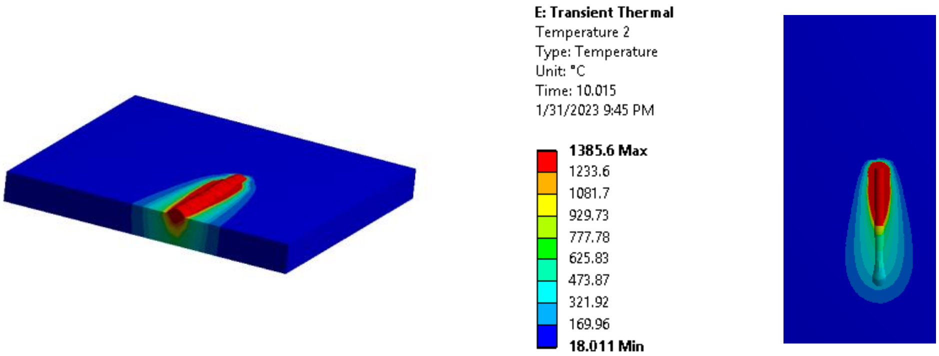

Figure 14. Section view of the HAZ in the centroid of Sample 1

In this case, a top and section view of the HAZ is depicted at the middle of the welding cycle. These results can be processed in any location of the model for further use in the structural design process.

4. Conclusions

The present paper proposes a new approach for evaluating the temperature gradients of the surfacing weld process. Experiments are conducted by considering 5 base metal samples that are made from S235JR steel with a thickness of 10 mm and a surface area of 20000 mm^2. The temperature curves are derived by considering the same current intensity but different gas flow rates. An infrared pyrometer is used for temperature acquisition at a location outside the welded joint. The resulting input and output variables are exported to the MATLAB environment where noise filtering and signal statistics processing are completed. A black box model is developed by employing the Nishikawa system identification approach. The numerator and denominator constants of the resulting transfer function are mapped to the welding parameters. A transient thermal analysis simulation model is employed for recreating the heat transfer of the surfacing weld process in ideal conditions. Afterwards, thermal conductance and capacitance are employed in accordance with the constants of the black box model. The resulting methodology has the ability to capture the temperature gradients of the process in any location.

REFERENCES

Arora, H., Singh, R. & Brar, G. S. (2019) Thermal and structural modeling of arc welding processes: A literature review. *Measurement and Control*. 52(7-8), 955-969. doi: 10.1177/0020294019857747.

Arsić, D. M., Ivanović, I., Sedmak, A., Lazić, M. M., Kalaba, D. V., Ceković, I. & Ratković, N. R. (2020) Experimental and numerical study of temperature field during hard-facing of different carbon steels. *Thermal Science*. 24(3), 2233-2241. doi: 10.2298/tsci190717338a.

Botez, I., Marin A., Sârbu I., Botez A. & Juc, V. (2011) *Electric Welding* [*Sudarea Electrică*]. Chișinău, Tehnica-Info Publishing House.

Cheng, Y., Yu, R., Zhou, Q., Chen, H., Yuan, W. & Zhang, Y. (2021) Real-time sensing of gas metal arc welding process–A literature review and analysis. *Journal of Manufacturing Processes*. 70, 452-469. doi: 10.1016/j.jmapro.2021.08.058.

Feng, Z., Ma, N., Li, W., Narasaki, K. & Lu, F. (2020) Efficient analysis of welding thermal conduction using the Newton–Raphson method, implicit method, and their combination. *The International Journal of Advanced Manufacturing Technology*. 111, 1929-1940. doi: 10.1007/s00170-020-06233-6.

Garbade, R. R. & Dhokey, N. B. (2021) Overview on Hardfacing Processes, Materials and Applications. In: *IOP Conference Series: Materials Science and Engineering (iCADMA 2020), 5-6 November 2020, Jawahar Lal Nehru Marg, India*. pp. 1-9. doi: 10.1088/1757-899X/1017/1/012033.

Hussin, M. H. & Lah, N. A. C. (2020) Weld bead surface defects formation and its implications–a review. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*. 72(2), 41-55. doi: 10.37934/arfmts.72.2.4155.

Jaidi, J. & Dutta, P. (2004) Three-dimensional turbulent weld pool convection in gas metal arc welding process. *Science and Technology of Welding and Joining*. 9(5), 407-414. doi: 10.1179/136217104225021814.

Junfeng, W. & Chunlong, D. (2012) Control method analysis based on welding process. In: *Proceedings* of the *Conference on Automatic Control and Artificial Intelligence ACAI 2012, 24-26 March 2012, Xiamen, China*. pp. 705-708. doi: 10.1049/cp.2012.1075.

Kumar, A., Rana, S., Gori, Y. & Sharma, N. K. (2021) Thermal Contact Conductance Prediction Using FEM-Based Computational Techniques. In: Kumar, A., Gori, Y., Dutt, N., Singla, Y. K. & Ambrish Maurya, A. (eds.) *Advanced Computational Methods in Mechanical and Materials Engineering.* Florida, FL, USA, CRC Press, pp. 183–217.

Mahiskar, G. I., Chadge, R. B., Ambade, S. P. & Patil, A. P. (2014) Thermo-mechanical analysis of multi-pass bead-on-plate welding. *Procedia Materials Science*. 5, 2522-2531. doi: 10.1016/j.mspro.2014.07.504.

Mičian, M., Winczek, J., Gucwa, M., Koňár, R., Málek, M. & Postawa, P. (2020) Investigation of welds and heat affected zones in weld surfacing steel plates taking into account the bead sequence. *Materials*. 13(24). 1-17. doi: 10.3390/ma13245666.

Moreira, P. M., Frazao, O., Tavares, S. M., de Figueiredo, M. A., Restivo, M. T., Santos, J. L. & de Castro, P. M. (2007) Temperature field acquisition during gas metal arc welding using thermocouples, thermography and fibre Bragg grating sensors. *Measurement Science and Technology*. 18(3), 877. doi: 10.1088/0957-0233/18/3/041.

Nishikawa, H. (2007) A first-order system approach for diffusion equation. I: Second-order residual-distribution schemes. *Journal of Computational Physics*. 227(1), 315-352. doi: 10.1016/j.jcp.2007.07.029.

Park, J., Martin, R. A., Kelly, J. D. & Hedengren, J. D. (2020) Benchmark temperature microcontroller for process dynamics and control. *Computers & Chemical Engineering*. 135, 1-13. doi: 10.1016/j.compchemeng.2020.106736.

Photoon, R. A. & Wichakool, W. (2015) System identification of Thermoelectric generator using a first order plus dead time model. In: *Proceedings of 2015 12th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology ECTI-CON 2015, 16-18 May 2015, Hua Hin, Thailand*. pp. 1-5. doi: 10.1109/ECTICon.2015.7207047.

Rincon-Tabares, J. S., Velasquez-Gonzalez, J. C., Ramirez-Tamayo, D., Montoya, A., Millwater, H. & Restrepo, D. (2022) Sensitivity Analysis for Transient Thermal Problems Using the Complex-Variable Finite Element Method. *Applied Sciences*. 12(5), 1-23. doi: 10.3390/app12052738.

Rose, S., Schnick, M., Hertel, M., Zschetzsche, J. & Füssel, U. (2010) Transient Simulation of Pulsed Gas Metal Arc Welding Processes and Experimental Validation. In: *International Scientific Colloquium Modelling for Material Processing, 16-17 September 2010, Riga, Latvia*. pp. 21-26.

Roshyara, N. R., Wilhelm, G., Semmler, U. & Meyer, A. (2011) Approximate analytical solution for the temperature field in welding. *Metallurgical and Materials Transactions B*. 42, 1253-1273. doi: 10.1007/s11663-011-9543-0.

Sachajdak, A., Słoma, J. & Szczygieł, I. (2018) Thermal model of the Gas Metal Arc Welding hardfacing process. *Applied Thermal Engineering*. 141, 378-385. doi: 10.1016/ j.applthermaleng.2018.05.120.

Schnick, M., Fuessel, U., Hertel, M., Spille-Kohoff, A. & Murphy, A. B. (2011) Numerical investigations of arc behaviour in gas metal arc welding using ANSYS CFX. *Frontiers of Materials Science*. 5, 98-108. doi: 10.1007/s11706-011-0134-4.

Sima, V., Hartescu, F. & Stanciu, A. (2017) Noi aplicaţii de calcul pentru identificarea sistemelor. *Romanian Journal of Information Technology and Automatic Control [Revista Română de Informatică şi Automatică]*. 27(2), 53-61.

Singh, S., Kumar, R., Goel, P. & Singh, H. (2022) Analysis of wear and hardness during surface hardfacing of alloy steel by thermal spraying, electric arc and TIG welding. In *Materials Today: Proceedings of 2nd International Conference on Functional Material, Manufacturing and Performances ICFNMP-2021, 17-18 September 2021, Jalandhar City, India*. pp. 1599-1605. doi: 10.1016/j.matpr.2021.09.122.

Stoicuta, O. & Mandrescu, C. (2012*) Identification of Systems* [*Identificarea sistemelor*]. Petroșani, Universitas Petroșani Publishing House.

Tapák, P. & Huba, M. (2016) Laboratory model of thermal plant identification and control. *IFAC-PapersOnLine*. 49(6), 28-33. doi: 10.1016/j.ifacol.2016.07.148.

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