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Original scientific paper

Prediction Model for Cladding of Ni-Alloys During CMT Welding Process by Using Fuzzy Logic

Iva DEANOVIĆ*, Dejan MARIĆ*, Ivan PEKO, Sanda ŠIMUNOVIĆ

Abstract: Maintaining stable conditions during cladding of Ni-alloys is of great importance for achieving a uniform quality of the cladded layer. As cladding of Ni-alloy is performed by the MAG-CMT welding process with a four-component gas on the base material (membrane wall), it cannot be always performed with the same tolerances. Therefore, the MAG-CMT welding process requires constant real-time monitoring and detection of faults in the cladded layer. This paper presents a model based on fuzzy logic. The created model is tested to confirm the proposed prediction model. The prediction accuracy was 93.67%, which proves that the created model can be used for cladding in new automated welding systems. Application of the obtained model shall enable the development of a monitoring system that can identify and classify certain defects occurring during the MAG-CMT welding process.

Keywords: cladding; geometric properties; MAG-CMT welding process; Ni-alloy; welding parameters

1 INTRODUCTION

When cladding process is performed with Ni-alloy, traditional cladding with MIG/MAG welding technology is not delivering good results, since there is an increase in the content of delta ferrite, causing the occurrence of high-temperature corrosion. The MAG-CMT process (Cold Metal Transfer) proves to be a better alternative, as it, with its method of droplet transfer, lowers the proportion of delta ferrite and reduces the possibility of high-temperature corrosion occurrence [1].

Nickel-based alloy (IN625) is usually used as a protection of 16Mo3 steel against high temperatures that occur in certain parts of plants or in waste incineration boilers, because the increased content of Ni, Cr and Mo in such alloy generally increases the corrosion resistance of the material [2-7].

The MAG-CMT procedure is usually applied in automatized processes primarily because of favorable ratio between low costs and high quality of manufactured parts, as well as shortened welding duration [8-10]. Therefore, cladding processes by MAG-CMT technology take place in automated and robotized systems in order to increase productivity of welding [11]. Machine learning has proven to be efficient in prediction and classification of welded joints and it delivers high percentage of accuracy. Fuzzy logic as one of the machine learning techniques is efficient, as proved by scalograms obtained on the basis of the Morlet wavelet transform of the welding current characteristics, and applied on classification and prediction of the depth of penetration in the welded joint during the gas metal arc welding (GMAW) [12].

Current research is based on the application of CMT cladding (3D printing) by using statistical method and Taguchi experimental design for the purpose of optimization of cladding output parameters and for determining of certain correlations between the welding parameters and the characteristics of the cladded layer [13]. Penetration of the welded joint is possible to be determined by using the classic method of preparing macro grindings of the welded joints. However, instead of using that classic method of destruction, prediction of the penetration depth of the welded joint is facilitated by CCD cameras and by determining the temperature in the local area of the welded joint by using Support Vector Machine (SVM). SVM as a model effectively predicts the penetration status of a welded joint made by the CMT welding process [14]. In addition to the SVM method, predicting penetration and porosity on the surface of the welded joint is also possible by using the combination of the Scheme Combining structural similarity index (SSIM) and the perceptual loss function, which improve the results of predicting the morphology of the melt, while another model is used for classification. The developed model applies 10 time intervals, and within each interval there are five prediction frames [15]. Welding parameters and monitoring of welding parameters (current and voltage characteristics, temperature, camera control, sound) are of great importance for creating a system for prediction and classification of the welded joint quality [16, 17]. Based on statistical indicators, two machine learning techniques, i.e. decision tree and support vector machine (SVM), are applied to classify welded joints as of their quality and to monitor defects, such as porosity, burn through and lack of penetration [18, 19].

In additive manufacturing processes, monitoring of the welding parameters for each layer is important in achieving the quality of the weld. Sensors for monitoring of the welding pool and sensors for measuring the main welding parameters are applied to design models based on residual-based network to quantitatively predict the weld reinforcement of the deposited layer [20]. The application of various statistical methods enables the assessment of influence of individual input parameters on responses, so for CMT welding additive manufacturing (WAAM) technology, the application of the Taguchi experimental design enables the insight into the quality of the welded surface with the application of self-made HNS wire with 0,99 wt% nitrogen content (n %) [21].

Nickel alloys are usually welded by TIG (Tungsten Inert Gas) procedure that causes large heat affected zone (HAZ), large deformations and residual stresses. In order to avoid poor performance of TIG procedure, Metal Active Gas - Cold Metal Transfer technology is recommended instead. MAG-CMT process facilitates reduced heat input during welding by applying certain changes in the welding parameters and by controlling wire flow in the weld pool. The selected MAG-CMT welding process has the same technological aspects as the conventional MAG (Metal Active Gas) welding process, however there is a new feature that allows the wire to go into and out of the weld pool. Such process allows exceptional stability and constant arc length [22-25]. In comparison with some other processes of Ni-alloy surfacing or cladding, MAG-CMT procedure exhibits greater advantages [26-31], such as greater arc stability, reduction of joints, usage of less power sources, reduction of the ratio of welded joint/heat affected zone, improved properties of the microstructure, reduction of residual stresses and deformations in welded joint, reduced delta ferrite content on the Ni-alloy surface, reduction of the cooling time of the welded joint, as well as 30% lower temperature when compared to conventional MIG/MAG (Metal Inert Gas/Metal Active Gas) process.

The MAG-CMT procedure is usually applied in automatized processes primarily because of favorable ratio between low costs and high quality of manufactured parts, as well as shortened welding duration [29, 32, 33]. Therefore, cladding processes by MAG-CMT technology take place in automated and robotized systems in order to increase productivity of welding [34, 35]. Characteristics of coated layers made of Ni-alloys are the following: delta ferrite content shall be less than 5 % on the surface of the Ni-alloy layer; there shall be minimal mixing of the base material and the filler material while maintaining appropriate level of bonding; uniform thickness shall be achieved along the entire coated surface, and rough transitions between passes shall be reduced [36]. The microstructure of Ni-alloy layer obtained by MAG-CMT process is dendritic, with increased content of nickel and chromium. The structure itself can change significantly if there is significant mixing of the base material and Ni-alloy cladding layer. In such case, Fe and C in the base material shall cause the change in the microstructure within the melting line zone [27, 38]. The type of shielding gas used for arc welding process proved to have great influence on obtaining different results related to cladding with Inconel 625 alloy [23, 36, 37].

Satisfactory results related to Ni-alloy cladding layer are achieved by applying the mixture of Ar + He + CO_2 + H_2 gasses, in which He and H_2 increase thermal conductivity and improve melt spreading. Small percentage of CO_2 enables good stability of the electric arc [37].

Monitoring of the main MAG-CMT welding parameters enables the evaluation of the welding process stability. Experiments are carried out to determine the possibility of using on-line monitoring of the welding process stability aiming to detect and possibly avoid defects and to achieve appropriate quality of the welded layer.

During MAG-CMT welding, two main phases take place, the arcing phase, which is the phase of constant voltage of the electric arc, during which there is no separation of the droplet in the pool. The second phase is the short circuit phase during which the droplet separates in the pool and mechanical pulling of the wire occurs. The change in the wire feed can range up to 70 Hz [39, 40]. The main welding parameters are:

- welding current strength, I / A
- welding voltage, U / V
- wire feed rate, vwire / m/min
- welding speed, vweld / m/min
- gas flow rate, fg / l/min
- droplet detachment frequency, fdroplet / Hz
- arc length correction, ALC / %
- dynamic control, DC / %
- distance of the contact conductor from the base material, ltip / mm.

New welding processes enable more precise control of the metal droplet transfer into the weld pool while maintaining the electric arc stability. There are various synergic controls of the MAG welding process developed so far, which means that the welding current is controlled by adjusting the wire feed rate. Such processes enable synchronization of power sources and wire feeders via microprocessors to maintain the arc stability. All welding sources depending on the wire flow rate and current strength apply almost the same processes [40, 41].

At the Fig. 1., there is a schematic presentation of the welding cycle, of the welding current strength, and the method of droplet detachment during CMT welding.

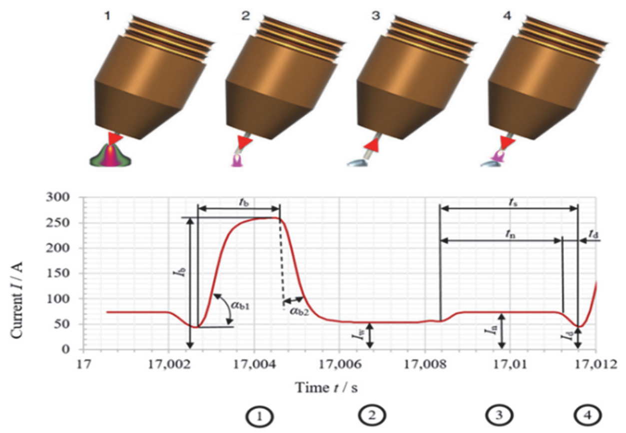


Figure1 The MAG-CMT process - 1. During arc ignition, the filler material moves towards the weld pool, 2. When filler material reaches the weld pool, the arc is extinguished - current is lowered, 3. Wire back-drawing detaches the droplet during short circuiting - short circuit remains with low current, 4. There is an additional wire back-drawing and the process is repeated continuously

The basic curve related to current strength in the MAG-CMT process consists of peak welding currents (I_b) lasting in the time interval (t_b), current at waiting of short-circuit (I_w) and short-circuit cycle time ($t_s = t_n + t$d). The short-circuit cycle consists of an increased value of the short-circuit current (I_n) that takes place in a certain time period (t_n) and the current strength at detachment (I_d) that takes place in the time interval (t_d). The rate of the current strength increase up to the peak values equals the angle $\alpha b1$, while the decrease rate from the peak current depends on the angle $\alpha b2$. Changing the values of all above-mentioned parameters can affect the quality of the welded joint [45, 46, 31].

2 EXPERIMENTAL TESTS

The cladding process was carried out on a Fronius VR 7000 CMT welding machine with a CNC interface. The experiment is carried out as shown in Fig. 2 and Fig. 3.

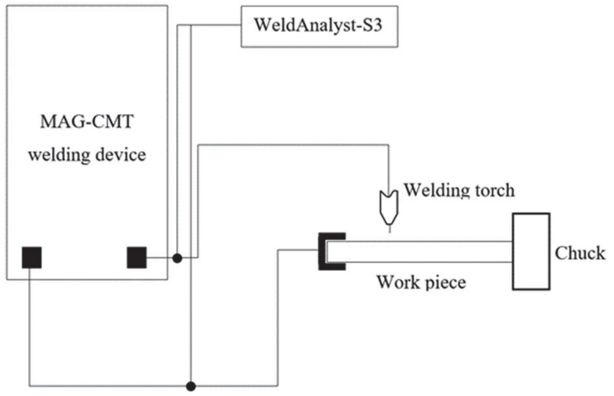


Figure 2 Equipment for experimental test

The test samples are prepared by cutting the segments out of the membrane wall, which consists of two tubes and the plate, as shown in Fig. 3. Both the tube and the plate are made of steel 16Mo3 (W. Nr. 1.5415). Electric arc welding (EPP) is applied to join the pieces. Prepared samples are shown in Fig. 4. Thermanit 625, Mat. No. 2.4831 with a diameter of 1.2 mm is used as a filler material. The material is highly resistant to corrosion and to cracking caused by corrosion at high temperatures that can reach up to 1100 °C [38]. The four-component gas CRONIGON Ni10 is used as a shielding gas.

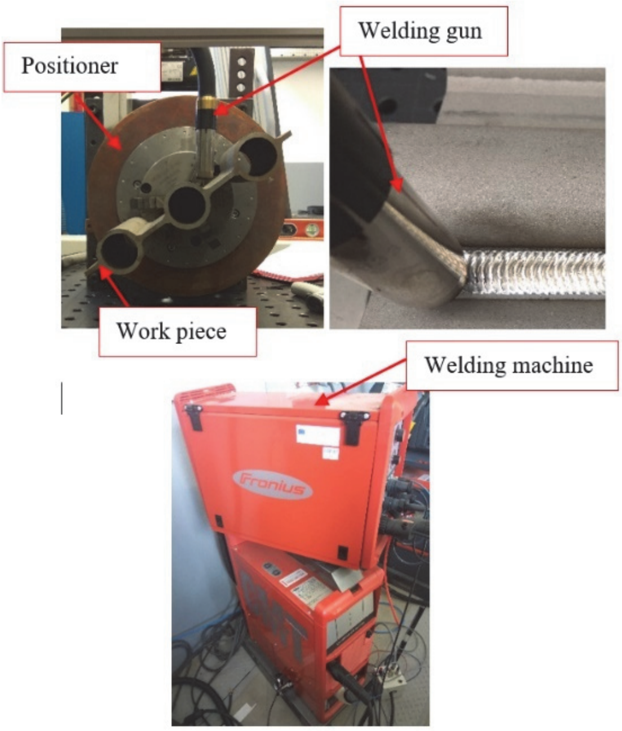


Figure 3 Experimental interface

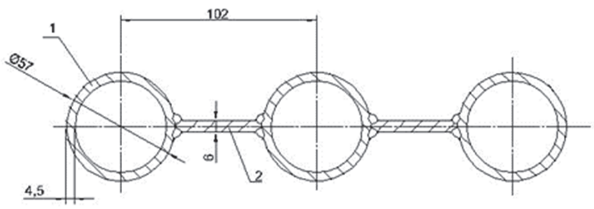


Figure 4 Layout of the membrane wall assembly

3 USAGE OF THE FUZZY LOGIC IN ADJUSTING THE HEIGHT OF THE CLADDED LAYER

The theory of fuzzy logic can be applied in researching of technical systems, as well as in other researches. The fuzzy logic method is a new approach to issues of managing more complex systems that are difficult to be presented and described by mathematical models. It is also suitable for systems with a larger number of inputs and outputs that exhibit ambiguity between interactions [47, 48]. In this paper fuzzy logic technique was applied to create expert system that will be able to predict influence of variable process parameters on analysed response. Also, that system will support monitoring and control of Ni alloys cladding process with the aim of enhancing its quality.

Input parameters (portion of helium, gas flow, arc length correction) are processed by the fuzzy logic to show their influence on the output parameter, i.e. on the height of the cladded layer (Tab. 1.).

Table 1 Central composite experimental design

INPUT PARAMETERS			OUTPUT
Portion of helium / %	Gas flow / l/min	ALC - Arc length correction / %	Height of the cladded layer / mm
15	30	0	2.2
15	10	30	2.05
15	10	0	1.98
15	20	0	2.18
15	30	30	2.46
15	20	30	2.23
30	20	0	2.35
30	30	30	2.43
30	20	0	2.3
30	20	0	2.25
30	20	30	2.4
30	30	0	2.29
30	20	30	2.28
30	10	30	2.51
30	10	0	2.48
30	20	30	2.41
45	10	0	2.36
45	20	30	2.54
45	30	0	2.58
45	30	30	2.65
45	20	0	2.45
45	10	30	2.48

According to the data contained in the Tab. 1., the input and output parameters are selected. In this experiment, the influence of input parameters on the output parameter is shown by using fuzzy logic. The fuzzy inference system consists of four steps [49]:

1. Fuzzification.
2. Inference.
3. Aggregation.
4. Defuzzification.

In the first phase of inference, a certain number of fuzzy sets are selected for each input parameter and their membership functions are defined. Functions are usually of triangular, trapezoidal and Gaussian shapes. The fuzzy rules are selected in the second phase. The form and number of fuzzy rules depend on the quality of available data. This is the key phase of this method. By applying these rules, distinct values of all input parameters are joined with as many membership functions of each output parameter as there are selected rules. Fig. 5 shows the structure of fuzzy inference for the selected input and output parameters.

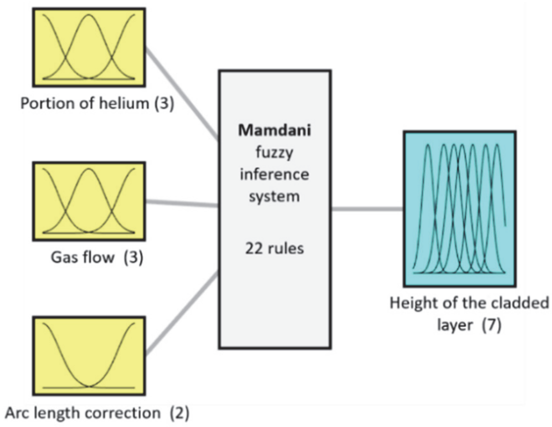


Figure 5 The fuzzy inference system

Membership functions for inputs and output are presented in Fig. 6. As it is visible, first two input parameters are described with three Gaussian membership functions: L (low), M (medium), H (high). Third input parameter was defined by two Gaussian membership functions: L (low) and H (high). The output was described by seven Gaussian membership functions: VL (very low), L (low), LM (low medium), M (medium), MH (medium high), H (high), VH (very high).

In the third step, values of the membership functions obtained in the previous step are unified for each output parameter. Thus, each output parameter gets one fuzzy set with defined membership functions. The FIS (fuzzy inference system) rules for evaluating the value of the output parameter are also determined.

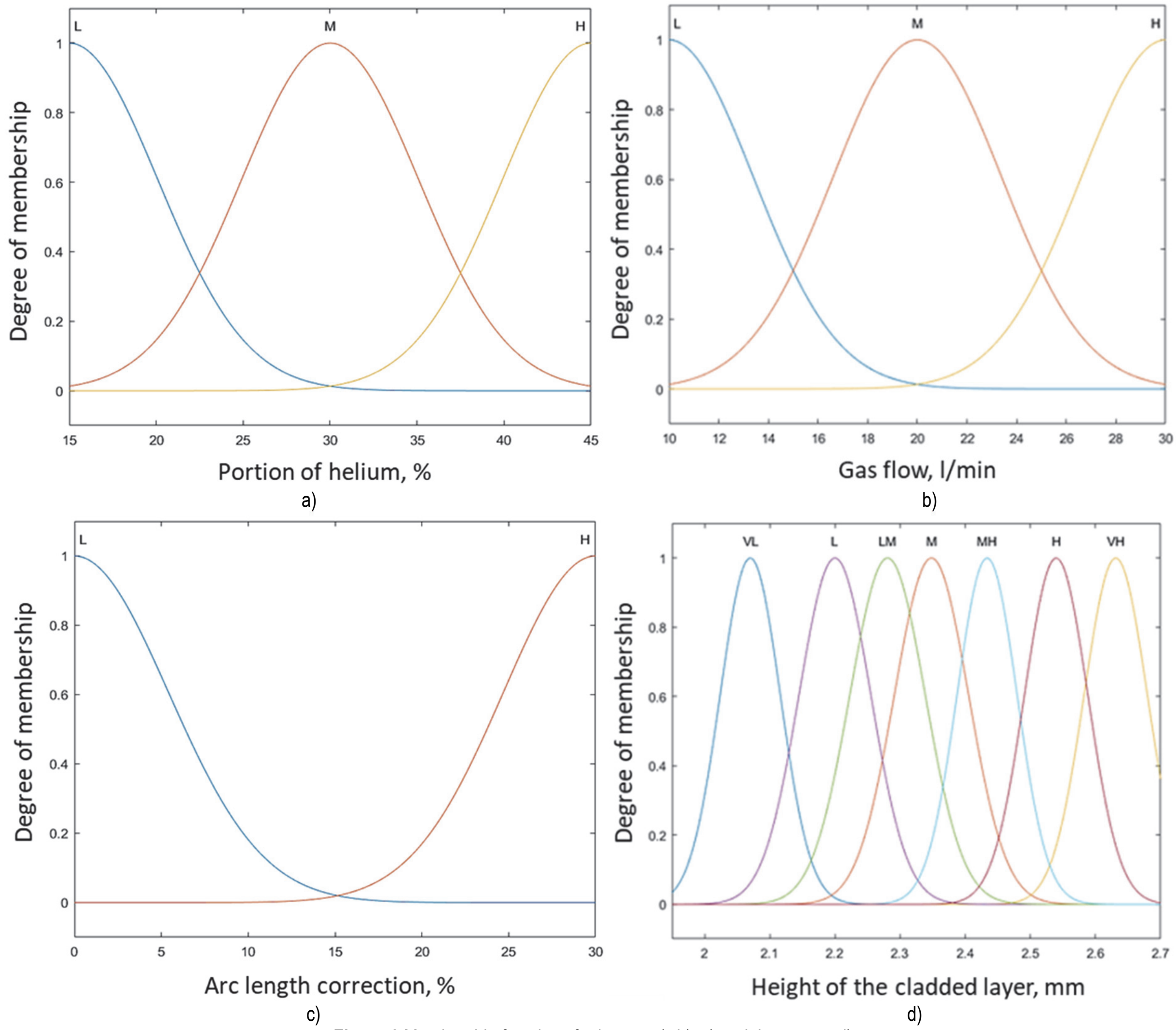


Figure 6 Membership functions for inputs: a), b), c) and the output: d)

In the fourth step, the fuzzy value of each output parameter is obtained, which can be shown by the inference diagram (Fig. 7.). Continuity is one of the most important properties of defuzzification. The defuzzification method is continuous if an infinitesimal change in the input parameter does not cause a sudden change in any output parameter, which is why the center-of-gravity method is chosen.

Calculations of the numerical value of the linguistic output parameter can be seen in the inference diagram. The gravity below the membership coefficient for individual linguistic set is superimposed into a new fuzzy set (shaded surface) and the center of gravity is calculated.

After fuzzy logic model was defined, its prediction accuracy needs to be confirmed. In order to do that comparison between experimental and fuzzy logic predicted output values was performed. As validation measures mean absolute percentage error (MAPE) and coefficient of determination (R^2) were applied, Fig. 8.

Results from Fig. 8 (MAPE: 0.014 %, R^2: 0.936) proved high prediction accuracy of developed fuzzy logic model of the cladded layer height response. Consequently, developed model can be further engaged for creation of response surface plots to discuss process parameters effects on analysed response values. Response surface plots are shown in Fig. 9. In these plots two process parameters are variable while the third was kept constant on levels 0% and 30%.

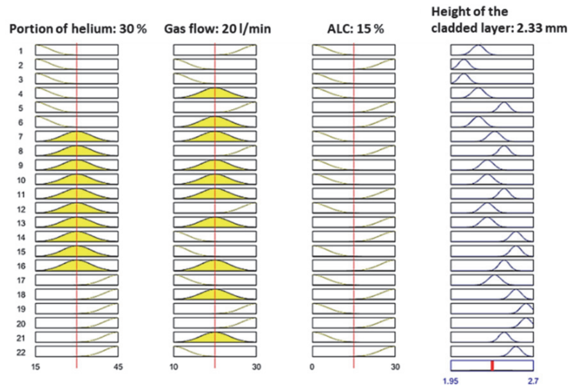
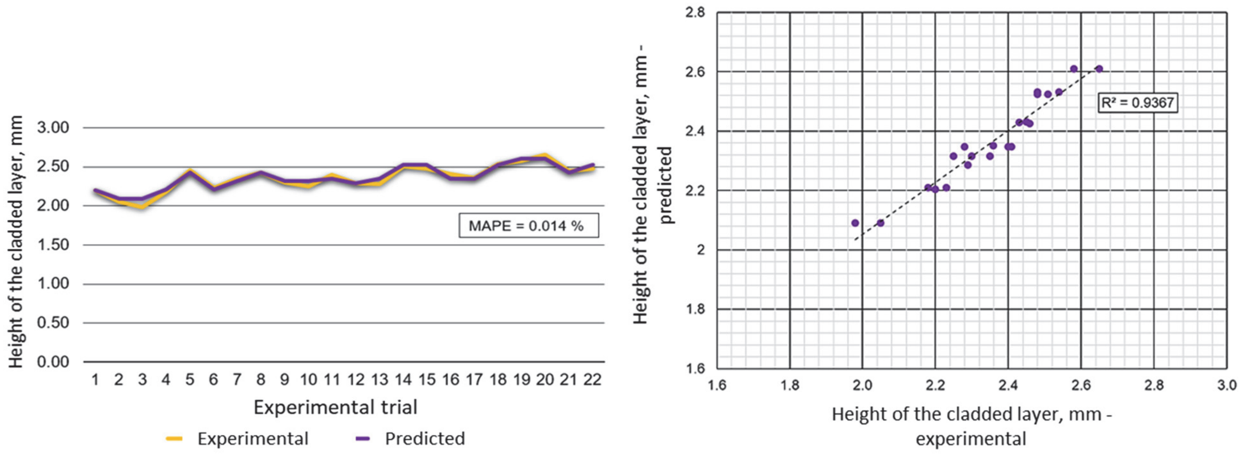


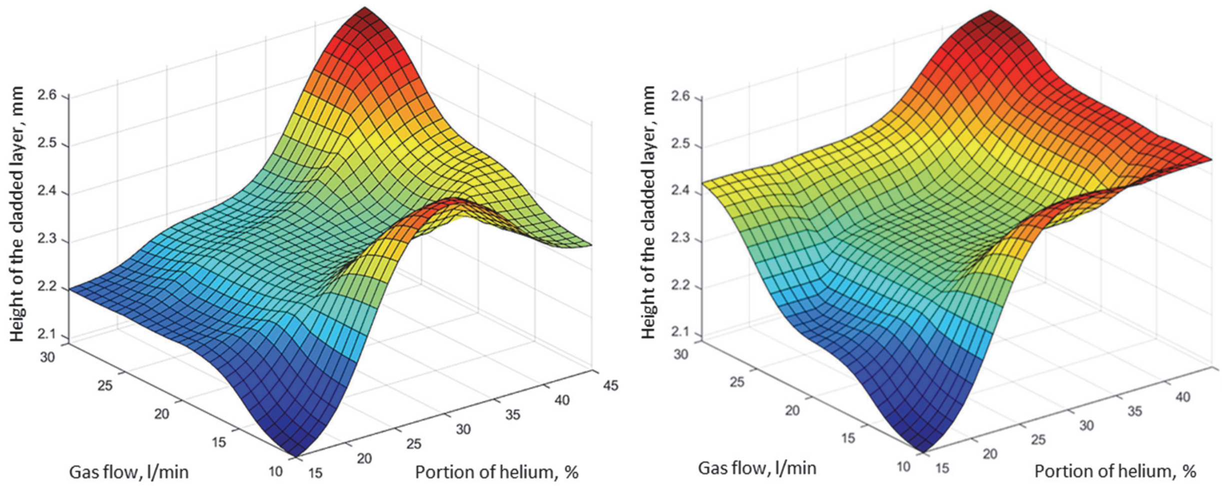
Figure 7 Fuzzy inference diagram



a) b)

Figure 8 Comparison of experimental and predicted output values with calculated: a) mean absolute percentage error (MAPE), b) coefficient of determination (R^2)

In Fig. 9a and Fig. 9b, it can be observed that the values of the height of the cladded layer of Ni-alloy are increased when it comes to the arc length correction of 30% compared to the arc length correction of 0%. Fig. 9a shows a decreasing trend in the value of the height of the cladded Ni-alloy layer with a decrease in the proportion of helium in the shielding gas mixture, and a decrease in gas flow when correcting the shown arc length from 0%. Fig. 9b shows a trend of decreasing the value of the height of the welded layer by reducing the proportion of helium in the shielding gas mixture, and by reducing the gas flow when correcting the length of the port by 30%.



a) b)

Figure 9 Response surfaces when arc length correction is constant at: a) 0 %, b) 30 %

4 CONCLUSION

Based on the model created with the help of the fuzzy logic technique obtained by on-line monitoring (welding current strength) of the MAG-CMT welding process, it is possible to evaluate the process stability and to classify the welded joints into two groups (good, bad) upon visual inspection of the cladded Ni-alloy. It is concluded that the ALC parameter - arc length correction significantly influences the process stability at changes in the portion of helium in the shielding gas mixture of 15%, 30% and 45%, whereby a more stable electric arc is obtained with an arc length correction of 30%. Prediction of these models were confirmed by MAPE and R^2 values.

A MAG-CMT welding machine is used for cladding of the samples, yet it should be investigated how other type of welding device with different current and voltage characteristics would influence the obtained results. Further research should also determine the influence of the defined parameters on the corrosion properties of Ni-alloy (Inconel 625), and the possibility of extending the service life of parts cladded with Ni-alloy. Based on the created models for the current-voltage characteristics, further research should be undertaken to improve the cladding in order to avoid defects and to achieve the required geometric characteristics of the cladded Ni-alloy.

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Contact information:

Iva DEANOVIĆ, mag. ing. mech.
(Corresponding author)
University of Zagreb,
Faculty of Mechanical Engineering and Naval Architecture in Zagreb,
Ivana Lučića 5, 10000 Zagreb, Croatia
E-mail: ivasamardzic@unisb.hr, iva.deanovic@fsb.unizg.hr

Dejan MARIĆ, PhD, Assistant Professor
(Corresponding author)
University of Slavonski Brod,
Mechanical Engineering Faculty in Slavonski Brod,
Trg Ivane Brlić Mažuranić 2, HR-35000 Slavonski Brod, Croatia
E-mail: dmaric@unisb.hr

Ivan PEKO, PhD, Assistant Professor
University of Split,
Faculty of science Split,
Ruđera Boškovića 33, 21000 Split, Hrvatska
E-mail: ipeko@pmfst.hr

Sanda ŠIMUNOVIĆ, mag. ing. mech.
University of Slavonski Brod,
Mechanical Engineering Faculty in Slavonski Brod,
Trg Ivane Brlić Mažuranić 2, HR-35000 Slavonski Brod, Croatia
E-mail: ssimunovic@unisb.hr