Indian Journal of Production and Thermal Engineering (IJPTE)
ISSN: 2582-8029(Online), Volume-1 Issue-1, December 2020

Underwater Twin-Arc Gas Metal Arc Welding for Low-Alloy Shipbuilding Steel

Aneliya Stoyanova*, Tatyana Mechkarova, Mariya Konsulova-Bakalova, Krastin Yordanov

Abstract*: The present work determines the impact of some of the main factors influencing the quality of the welding joint during underwater welding in gas metal arc welding (GMAW) with two arcs supplied by two power sources. The variables chosen are: the alteration of the currents in the welding arcs, the distance between the arcs and the welding speed. The problem is solved by mathematical planning of the experiment whereby the optimization parameter is the hardness in the zone of thermal influence.The experiments were carried out on the basis of the accepted Common Central Composite Plan (CCCP) with the selected factors and levels of variation. The processing of the statistical data through the Microsoft Office Excel software enables the calculation of the regression coefficients and the regression equation.

***Keywords*: Underwater Twin-Arc Welding; Gas Metal Arc Welding (GMAW); Low-Alloy Shipbuilding Steel.**

I. INTRODUCTION

Underwater technologies have an important place in the strategy of developed maritime countries for exploration of shelf zones – sources of practically inexhaustible natural resources. That is why the development of underwater welding technologies for metals and alloys is extremely important, because without it, the operation, construction, emergency repair and maintenance of oil and other underwater facilities would be impossible [1].

Numerous methods for underwater welding of metals are known, but the practical application of each of them is mostly determined by their basic technological and other characteristics, as well as by the specific conditions in each case. The need for research in this field is imperative, as a number of high-performance welding methods in gas environment have recently been developed and are currently being implemented, which could also be applied underwater [2, 3].

Manuscript received on 06 November 2020 | Revised Manuscript received on 30 November 2020 | Manuscript Accepted on 15 December 2020 | Manuscript published on 30 December 2020.

***** Correspondence Author

Aneliya Stoyanova*, Assistant, Department of Technology of Machine Tools and Manufacturing, Technical University of Varna, Bulgaria, e-mail: tatuna10@abv.bg

Tatyana Mechkarova, Assistant, Department of Materials Science and Technology, Technical University of Varna, Bulgaria, e-mail:tatqna13@abv.bg

Mariya Konsulova-Bakalova, Prof. assistant, Department of Technology of Machine Tools and Manufacturing, Technical University of Varna, Bulgaria, e-mail: mbakalova@tu-varna.bg

Krastin Yordanov, Prof. assistant, Department of Thermal Engineering, Technical University of Varna, Bulgaria, e-mail: krastin_yordanov@tu-varna.bg

At the same time, a number of issues have not been unified yet, such as: the structural parameters of the elements of the underwater welding equipment, its technological and resource capabilities, and last but not least, the electrical safety in the work area when working with equipment of this kind. The solution to these issues is of high priority given that there are already real technical and technological prerequisites for practical implementation of the method – high level of welding equipment and technology, availability of cutting edge modern equipment, advanced facilities and trained specialists [1, 4].

Therefore, the present work represents a stage of investigation related to the study of the processes occurring in underwater twin-arc welding in gas metal arc welding (GMAW) [1, 2 and 4]. In the references cited, the supply to the two arcs comes from a single power source. However, in many cases it is necessary to carry out twin-arc underwater welding with two power sources (Figure 1).

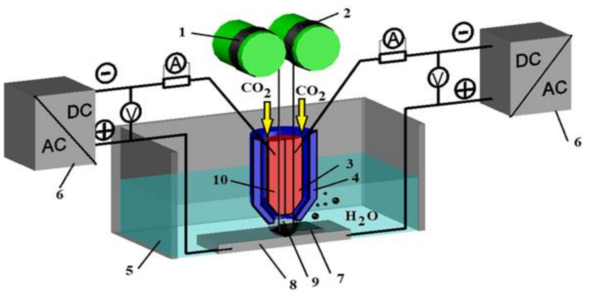


Fig. 1.Schematic design of the experimental equipment for twin-arc underwater welding with two power sources: 1, 2- electrode wires; 3, 10- power-carrying nozzles; 4- protection nozzle; 5- water basin; 6- power sources; 7- metal of the seam; 8- base metal; 9- steam-gas bubble

Figure 2 shows the design of the burner used for underwater welding. Welding is carried out with the simultaneous operation of two welding sources.

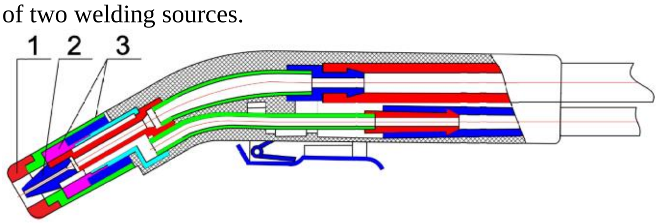


Fig. 2.Design of underwater welding burner: 1- protective gas nozzle; 2- power-carrying nozzle; 3- insulators

Welding power sources, type IZA-G500, have a transformed electrical circuit providing a static volt-ampere characteristic with increased voltage in idle mode [2], (Figure 3).

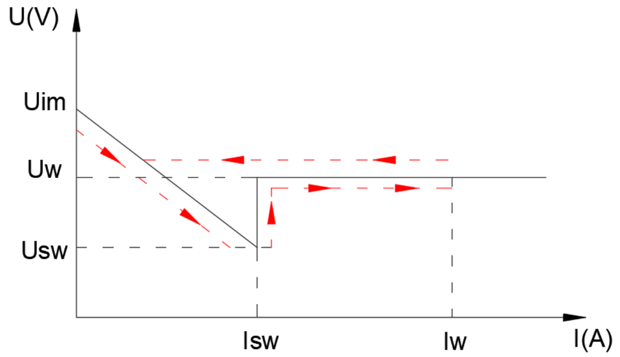


Fig. 3. Combined static volt-ampere characteristic: Uim-voltage in idle mode; Uw- working voltage; Iw- working current; Isw- switching current; Usw- switching voltage

II. EXPERIMENTAL TEST

The experimental tests were carried out in a fresh water basin with dimensions 1000x500x500mm, as shown in Figure 4, at a working depth of 200mm and the following conditions:

- base metal for welding: shipbuilding steel, grade S355N as per EN 10025-3 :2004 (samples sized 180x140x14 mm);
- electrode wire, brand SG3 as per DIN 8559 (AWS A.5.18-79) (diameter of electrode wires 1.2 and 1.6 mm)
- distance between the protective gas nozzles and the base metal: 5mm;
- stick-out of electrode wires: 14mm;
- type of welding current: DC+;
- type of protective gas: CO_2, 100% (C1 DIN439);
- velocity of electrode wire feed:V_{W1}= 8.8 m/min, V_{W2}=18.2 m/min;
- consumption of protective gas: 30 dm^3/min;
- diameter of the protective nozzles: 2x12 mm;
- velocity of welding: up to 15.0 m/h;
- maximum voltage in idle mode of the power sources: 70÷80 V;
- length of the welding chain: 10 m;
- distance between electrode wires: 16÷20 mm.

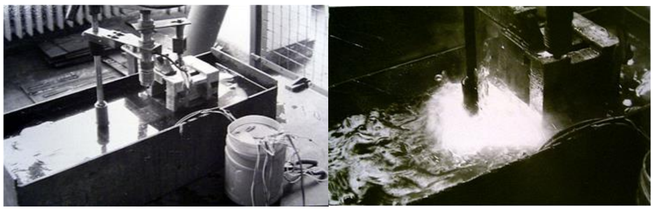


Fig. 4.Experimental basin with a welding burner.

The chemical composition and mechanical characteristics of the base metal is shown in Table- I and Table- II [5, 6] and of the electrode wires in Table- III [7].

Table- I: Chemical composition of the base metal, %

Chemical elements	C	Si	Mn	P	S	N	Al	Cu
Value, %	0.20	0.50	0.9-1.65	0.03	0.025	0.015	0.020	0.55

Chemical elements	Cr	Ni	Mo	Nb	V	Ti	Fe	CEV
Value, %	0.30	0.50	0.10	0.05	0.12	0.05	95.5- 99.15	0.43-0.45

Table- II: Mechanical characteristics of the base metal

Parameters	Tensile strength, Rm, MPa	Yield strength, Re, MPa	Elongation at yield, A, %	Brinell Hardness, HB
S355N	470-630	355	22	160

Table- III: Chemical composition and mechanical characteristics of electrode wires, %

Chemical elements	C	Si	Mn	Tensile strength, Rm, MPa	Yield strength, Re, MPa	Elongation at yield, A, %
Value, %	0.07-0.15	0.80-1.15	1.40-1.85	550	430	30

The present study is intended to determine the impact of the coefficient that accounts for the ratio of welding currents in arcs, the distance between them and the velocity of welding, over the alteration of HV5 hardnesses in the heat affected zone during twin-arc welding. The microhardness measurements in depth of the sample were performed in this study according to the Vickers method as per BDS EN 23878:2000 and BDS EN ISO 6507-1:2006.

Figure 5 shows the welding seams as follows: in 1 are the samples welded in air; in 3, 4 the samples welded in air but partially submerged in water; and in 5, 6 and 7 the samples welded under water, with GMAW.

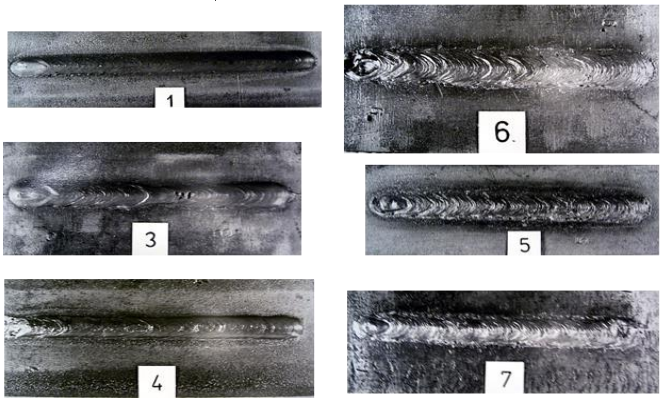


Fig. 5.Outer appearance of welding seams: 1- welding in air; 3, 4- welding under partial submersion in water; 5, 6 and 7- underwater welding.

It is obvious from Figure 5 that the welding seams obtained in GMA underwater welding with two arcs are properly shaped, with a low degree of layering and without the presence of macrodefects, which is evidence that the welding modes have been correctly selected.

The purpose of the experiment is to identify the technological capabilities of the GMA underwater welding method with two arcs and to optimize the mode parameters by using the methods of experiment planning and mathematical statistics.

III. EXPERIMENTAL - STATISTICAL STUDY IN THE PROCESS OF UNDERWATER TWIN-ARC GMAW

Regression analysis is an important statistical method for the analysis of technical data.

It enables the identification and characterization of relationships among multiple factors. It also enables the identification of prognostically relevant risk factors and the calculation of risk scores for individual prognostication.

The purpose of statistical evaluation of technical data is often to describe relationships between two variables or among several variables.

The purpose of the methodology is to identify the technological opportunities to use the methods of experiment planning and mathematical statistics in order to optimize the mode parameters of the method for underwater twin-arc GMAW [8].

When choosing a specific plan for the experiments, a compromise is necessary to be made in the requirements for: the accuracy of mathematical description of the process; the ease of experimental data processing; minimum number of experiments. An experiment plan is considered for construction of a model of the 2nd order [9], and it is an excerpt from the rows of the full factor experiment 3к, which is of the kind (1). In addition, each factor must be altered at no less than three levels. The results of the experiments are calculated from the selected estimates of the model coefficients and the regression equation (4) is compiled [10]:

where: Y is the true value of the response;

$$Y = \beta_0 + \sum_{1 \le i \le k} \beta_i X_i + \sum_{1 \le i \le j \le k} \beta_{ij} X_i X_j + \sum_{1 \le i \le k} \beta_{ii} X_i^2$$

(1)

$\beta_i, \beta_{ij}, \beta_{ii}$ - true value of the coefficients;

k – number of factors

The number of members in this model is (2):

$$C_{k+2}^{k} = \frac{(k+2)!}{2!} = \frac{(k+1)(k+2)}{2}$$

(2)

therefore, the number of tests N (3) for the construction should not be less than [10]:

$$N \ge \frac{(k+1)(k+2)}{2}$$

(3)

Some of the most cost-effective plans in view of the number of tests have been proposed by Hartley, Rechtschaffner. It turns out that it is possible to set plans, the number of tests in which is either equal to the number of coefficients in the model or slightly larger. In the specific case, we selected that the number of tests required for our plan be 11 and 4 more were conducted to determine the repeatability of the results obtained [10].

As parameter of optimization is selected the alteration of the hardness (HV5) in the heat affected zone of the welding joint. It is determined according to the requirements of the standard TGL ST RGW 470-77, with input factors:

x_1- the coefficient that accounts for the alteration of the welding currents in both arcs k (4):

$$k = \frac{I_2}{I_1 + I_2} \qquad (4)$$

where:

I_1- welding current in the first electrode wire, A;

I_2- welding current in the second electrode wire, A;

x_2- distance between the electrode wires, S, mm

x_3- velocity of welding, V_w, m/h

Correlation coefficients provide information about the strength and direction of a relationship between two continuous variables. No distinction between the explaining variable and the variable to be explained is necessary.

Table- IV shows the levels of alteration of the factors and Table- V shows the values of the experimental results for the optimization parameter:

- n be the number of observations (e.g., subjects in the study);
- Yi be the observed value of the dependent variable for the i-th observation;
- Ŷi be the mean of all n observations of the dependent variable.

Table- IV: Levels of factor alteration

Factors (levels of alteration)	Coefficient: k	Distance between electrode wires, S, mm	Velocity of welding, V_w, m/h
	x_1	x_2	x_3
Basic level; xo	0.53	18	11
Interval of alteration; Δx	0,01	2	2.5
Top level: xi=+1; i=1.2	0.54	20	13.5
Bottom level: x_i=-1; x=1.2	0.52	16	8.5

Table- V: Experimental results for the optimization parameter

№ of tests n	Factors (levels of alteration)										Y_1	Y_2	Y_3	$\overline{Y}$
	X_0	X_1	X_2	X_3	$X_1.X_2$	$X_1.X_3$	$X_2.X_3$	X_1^2	X_2^2	X_3^2	Optimization parameter, HV5			
1	1	-1	-1	-1	1	1	1	1	1	1	287	286	282	285
2	1	-1	1	1	-1	-1	1	1	1	1	305	304	300	303
3	1	1	-1	1	-1	1	-1	1	1	1	282	281	277	280
4	1	1	1	-1	1	-1	-1	1	1	1	288	287	283	286
5	1	-1	-1	1	1	-1	-1	1	1	1	292	291	287	290
6	1	1	-1	-1	-1	-1	1	1	1	1	300	299	295	298
7	1	-1	1	-1	-1	1	-1	1	1	1	284	283	279	282
8	1	1	0	0	0	0	0	1	0	0	289	288	284	287
9	1	0	1	0	0	0	0	0	1	0	293	292	288	291
10	1	0	0	1	0	0	0	0	0	1	272	271	267	270
11	1	0	0	0	0	0	0	0	0	0	308	307	303	306

Regression analysis is a type of statistical evaluation that enables three things:

- Description: Relationships among the dependent variables and the independent variables can be statistically described by means of regression analysis.
- Estimation: The values of the dependent variables can be estimated from the observed values of the independent variables.
- Prognostication: Risk factors that influence the outcome can be identified, and individual prognoses can be determined.

Regression analysis employs a model that describes the relationships between the dependent variables and the independent variables in a simplified mathematical form.

The experiments were performed with the following mode parameters:

- welding current I_w=260÷360A;
- working voltage, U_w=42÷46V;
- working depth of water, h=200mm.

In many cases, the contribution of a single independent variable does not alone suffice to explain the dependent variable Y. If this is so, one can perform a multivariable linear regression to study the effect of multiple variables on the dependent variable.

In the multivariable regression model, the dependent variable is described as a linear function of the independent variables Xi, as follows (1). The model permits the computation of a regression coefficient bi for each independent variable Xi.

After determining the correlations and coefficients in front of the unknowns, the regression equation (5) takes the following form [11]:

$$Y(X_1,X_2,X_3)=295.05-4.92*X_1-3.17*X_2-2.67*X_3-4.99*X_1*X_2-8.49*X_1*X_3+1.26*X_2*X_3+2.34*X_1*X_1+4.59*X_2*X_2-16.91*X_3*X_3 \quad (5)$$

Linear regression is used to study the linear relationship between a dependent variable Y and one or more independent variables X. Each of the coefficients bi reflects the effect of the corresponding individual independent variable Xi on Y, where the potential influences of the remaining independent variables on Xi have been taken into account, i.e., eliminated by an additional computation.

The dependent variable Y must be continuous, while the independent variables may be either continuous, binary, or categorical. The initial judgment of a possible relationship between two continuous variables should always be made on the basis of a scatter plot (scatter graph). This type of plot will show whether the relationship is linear or nonlinear.

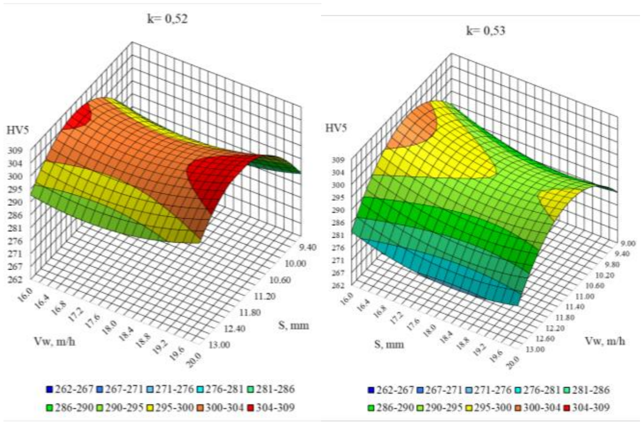
For the regression model to be robust and to explain Y as well as possible, it should include only independent variables that explain a large portion of the variance in Y. Variable selection can be performed so that only such independent variables are included.

Figure 6 shows diagrams of isolines which indicate the alteration of the HV5 hardness in the HAZ (heat affected zone) as a function of the coefficient k, the distance between the electric welding arcs S and the velocity of welding V_w. In each of the diagram, HV5 is a function of two factors at constant (optimal) values of the other two (zero coordinates of the new coordinate system) [12, 13].

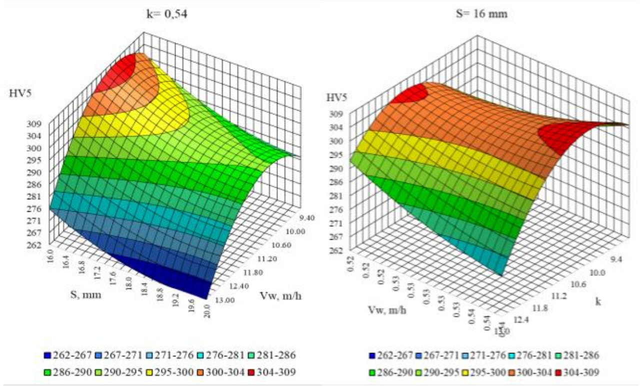
By the calculations made to determine the Fisher criterion (F – criterion) [11, 12 and 13], we obtain for F=11.09 <Fkr (19.37), so we find out that the model is adequate and can be used for prediction.

From the mathematical model thus obtained, after solving the regression equation, it can be seen that the minimum hardness HV5 in the HAZ with GMA underwater welding with two arcs is obtained at the following levels of the factors:

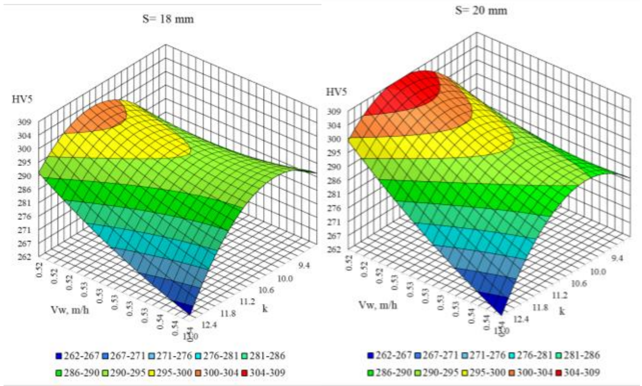
- x_1- top level, k=0,54 (coefficient k);
- x_2- bottom level, S=16 mm (distance between electrode wires);
- x_3- top level, Vw=13.5 m/h (velocity of welding).



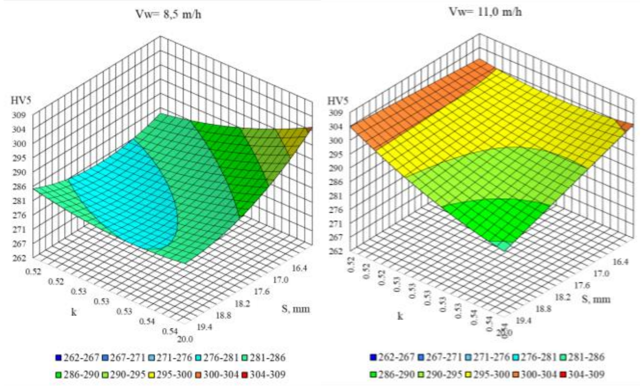
a) $\bar{y}$ =f(X_2, X_3) at X_1=-1 b) $\bar{y}$ =f(X_2, X_3) at X_1=0



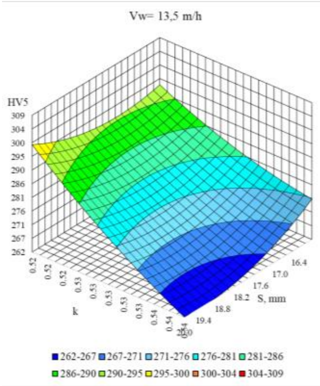
c) $\bar{y}$ =f(X_2, X_3) at X_1=+1 d) $\bar{y}$ =f(X_1, X_3) at X_2=-1



e) $\bar{y}$ =f(X_1, X_3) at X_2=0 f) $\bar{y}$ =f(X_1, X_3) at X_2=+1



j) $\bar{y}$ =f(X_1, X_2) at X_3=-1 h) $\bar{y}$ =f(X_1, X_2) at X_3=0



k) $\overline{y}$ =f(X_1, X_2) at X_3=+1

Fig. 6.Correlations between HV5 hardness after underwater welding with two arcs in protective gas environment and the technological parameters.

In this way, multivariable regression analysis permits the study of multiple independent variables at the same time, with adjustment of their regression coefficients for possible confounding effects between variables.

Multivariable analysis does more than describe a statistical relationship; it also permits individual prognostication and the evaluation. A linear regression model can be used, for instance, to determine the optimal values HV5.

Technical questions often involve the effect of a very large number of factors (independent variables). The goal of statistical analysis is to find out which of these factors truly have an effect on the dependent variable. The art of statistical evaluation lies in finding the variables that best explain the dependent variable.

One way to carry out a multivariable regression is to include all potentially relevant independent variables in the model (complete model). The problem with this method is that the number of observations that can practically be made is often less than the model requires. In general, the number of observations should be at least 20 times greater than the number of variables under study.

Moreover, if too many irrelevant variables are included in the model, overadjustment is likely to be the result: that is, some of the irrelevant independent variables will be found to have an apparent effect, purely by chance. The inclusion of irrelevant independent variables in the model will indeed allow a better fit with the data set under study, but, because of random effects, the findings will not generally be applicable outside of this data set (table IV and V). The inclusion of irrelevant independent variables also strongly distorts the determination coefficient, so that it no longer provides a useful index of the quality of fit between the model and the data.

IV. CONCLUSION

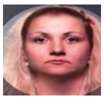
The performance and interpretation of linear regression analysis are subject to a variety of pitfalls, which are discussed here in detail. The reader is made aware of common errors of interpretation through practical examples. Both the opportunities for applying linear regression analysis and its limitations are presented.

1. A twin-arc GMA underwater welding of 14mm thick shipbuilding steel S355N has been implemented in protective gas environment of carbon dioxide with two power sources. From the conducted experiment welding joints have been obtained without the presence of macrodefects in the formed seams, which is evidence that the welding modes were correctly selected.
2. A methodology has been developed for experimental-statistical investigation of the correlation between the technological parameters of the process of twin-arc GMA underwater welding and their impact on the measured HV5 hardness in the heat affected zone of the welded samples has been determined.
3. A mathematical description has been made of the process of twin-arc GMA underwater welding with two sources of current. The regression equation has been obtained for the hardness in the HAZ with altering of the coefficients that account for the ratio of the currents in the arcs (coefficient k), the distance between them (parameter S) and the velocity of welding (Vw).
4. The analysis of the graphical dependencies regarding the ranking and the significance of the three factors k, S, Vw as well as their impact on HV5 show that, despite the fact that some of the coordinates of the optimum point are far beyond the boundaries of the factor space, the impact of the factors on the hardness after twin-arc GMA underwater welding is clearly visible and the tendency of the opportunities for its reduction is evident.

REFERENCES

1. Nikov N.Y., Dichev Pl.D., Method and device for gas metal arc welding and cutting of metals under water, Certificate of authorship №052246/29 May 1982.
2. Dichev Pl.D., Rafailov A.P., Research on the process of gas metal arc underwater welding, performed with a power source with complex V-A characteristic, Machine-building Equipment and Technologies, NTS-Varna, TU-Varna, №2, 2006, pp. 48-52.
3. Dichev Pl.D., Rafailov A.P., Electro-oxygen twin-arc cutting of shipbuilding steel S355N under water, Machine-building Equipment and Technologies, NTS-Varna, TU-Varna, №2, 2006, pp. 44-47.
4. Seyffarth P., ATLAS, Schweiss- ZTU- Schaubilder, Band I, Wilhelm-Pieck- Universitat, Rostock, 1978, pp. 36-59.
5. Spasova D., „Capillary Casting of Iron-Based Alloys“, Advances in Materials and Processing Technologies , 07 Nov 2016, Volume: 2, Issue: 03, pages 361 – 366.
6. Handbook: Steel and alloys grades and properties: http://aluminumwelding.sell.everychina.com/p-92979922-din-8559-sg3-welding-wire.html
7. Handbook: Steel and alloys grades and properties: http://www.steelnumber.com/en/steel_composition_eu.php?name_id=18
8. Bozhanov E.S., Statistical Methods for Modelling and Optimization of Multifactor Objects, TEHNIKA, Sofia, 1973
9. Vuchkov I.N., Experimental Research and Identification, Tehnika, Sofia, 1990, p.320.
10. Vuchkov I., Optimal Planning for Experimental Research, S., Tehnika, 1978, p.232.
11. Vuchkov, I., Stoyanov, S. Mathematical modelling and optimization of technological objects. S., Tehnika, 1986, p.341.
12. Vuchkov, I., Stoyanov, S., Velev K. Instructions for laboratory exercises in mathematical modelling and optimization of technological objects. S., Tehnika, 1986
13. Ivanov G., Kyuchukova V. Instructions for solving mathematical optimization problems. S., Kliment Ohridski, 1989

AUTHORS PROFILE



Aneliya M. Stoyanova is assistant of Department of Technology of Machine Tools and Manufacturing at Technical University of Varna. She is a member of the 'Union of Scientists'. She also teaches students at Technical University - Varna, namely the course "Interchangeability and technical measurements" and "Welding production theory". She research concerns simulation (especially its statistical design and analysis),welding and cutting machines and samples.

Tatyana M. Mechkarova is assistant of Department of Materials Science at Technical University of Varna. She is a member of the 'Union of Scientists'. She also teaches students at Technical University - Varna, namely the course " Design Engineering and CAD analysis.

Senior assistant prof. **Mariya Konsulova-Bakalova** is a member of Department of Manufacturing Technologies and Machine Tools at Technical University of Varna, and 'Union of Scientists' - Varna. Some of the courses she teaches are: Basics of Computer Aided Design in Mechanical Engineering, 3D Modelling, Computer Systems for Mechanical Engineering, Optimal Design of Mechanical Elements. Her main scientific interests are in the field of simulation modeling and analysis.

Krastin K. Yordanov is prof. assistant of Department of Thermal Engineering at Technical University of Varna, Bulgaria. He earned his PhD in 2017. with a degree in "Theoretical and Applied Heat Engineering" at the Technical University of Varna. Has published in local and foreign magazines in the fields of Modeling and Simulation, Control Systems Engineering, Engineering Thermodynamics, Finite Element Analysis and others. They are available in the following databases: https://orcid.org/0000-0002-6714-6480; Scopus Author ID: 57196041130; https://scholar.google.com/citations?view_op=list_works&hl=en&user=FwBAzGwAAAAJ. Has participated in four projects in the areas of measuring physical dimensions, visualizing them for easier understanding by a wide range of people, simulating physical processes with CAE products and obtaining quantitative and value results, developing functioning prototypes and other. Member of the "Union of Scientists" in Bulgaria.