TAGUCHI METHOD IN ELECTRON BEAM WELDING WIDTH STUDY

Adriana Munteanu
"Gheorghe Asachi" Technical University of Iaşi - Romania, Department of Machine Tools, adycypmunteanu@yahoo.com

ABSTRACT: The quality of the electron beam joints depends on a great number of parameters both of the workpiece material and of the beam. To reduce the input parameters one can use the Taguchi method. According to Taguchi method for the study of the influence of beam parameters and the welding parameters on the electron beam output parameters like weld width, one can reduce the number of experiences without losing the observations precision. An important advantage of this method is attention accorded to the possible interactions between factors highlight input into the process. The optimization of the system response involves finding the minimum of all possible answers in this case, the smallest weld width value.

KEY WORDS: welding width, electron beam welding, Taguchi method.

1. INTRODUCTION

The nonconventional machining technologies are technologies based on other principles than those found at the base of the conventional technologies and which generally speaking use a distinct energy transfer principle in order to process and thus to use some kinds of indirect energy. The development of nonconventional technologies came as a necessity to the quick increase of the use of special materials, with special proprieties (high hardness and strength) and complex shape, which are difficult to machine or even it is not possible to machine them by the so called conventional technologies. The nonconventional technologies are multidisciplinary, the variety of physical and chemical phenomena leading to specific equipments, determined a real revolution in machining areas and the level of knowledge has exceed the strict technical knowledge, involving knowledge of physics, materials science, electronics, computer science etc. Almost any solid material can be machined in order to obtain an acceptable surface finish, with some limitations regarding the tools and the machines, by conventional machining methods. This limitation can be removed in case of use nonconventional machining methods. The nonconventional technologies do not involve direct contact of tool and workpiece, so that the tool wear could be eliminated or at least diminished and the operation is quieter. But the high cost, the complex set-up and the necessity of using skilled operators are some of the disadvantages of the nonconventional technologies.

A brief classification of the nonconventional technologies can be observed in figure 1. One of the electro-thermal processes used since 1954, when it is mentioned the first time within the welding processes, is the electron beam process. This process is based on the fact that electrons can be accelerated and they could generate a narrow beam in an electric field. The beam can be focused and directed by an electrostatic or electromagnetic system.

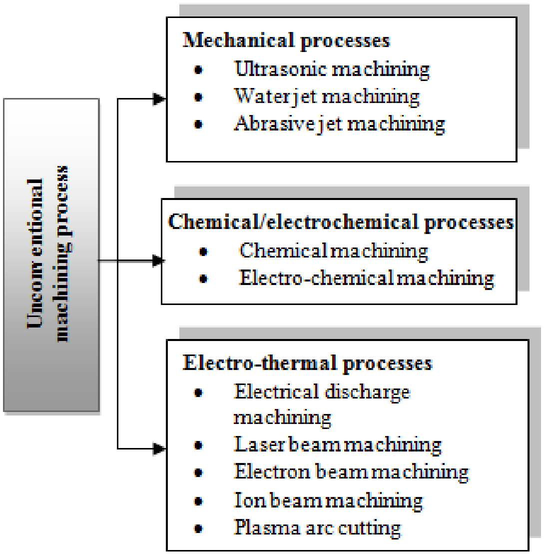

Figure 1. Unconventional process classification

One can mention many ways of electron beam manufacturing processes classification; one of these classifications takes into account the changes developed in workpieces, the changes being dependent, to some extent, on the time of action of the electron beam. Another classification takes into account the size of the depression (vacuum) for process materializing, and another one of classifications is based on the analysis of characteristics of the electron beam.

The impact of the electron beam on the surface layer to be machined triggers highly complex process interactions, that depend on the transfer of kinetic energy of the electrons to the workpiece surface layer, together with the brake, deflection and, ultimately, blockage of electrons to a depth possible to be previously determined.

The latest scientific articles [7, 8] regarding electron beam welding emphasized the importance of the input and the output process input factors. An important aspect is the difference between the physical and technological factors and of course the fact that is much easier to measure and control the sizes of technological factors than the size of the physical ones. In this direction, technological experiments are leaded demonstrating the influence of the technological factors on the characteristics of the resulted welds. The welds development is related with the development of a set of welding factors on a dedicated welding machine [9] and, thus, the optimization of the welding process is related to distinct approaches. In order to show the influence exerted by various factors on electron beam weld width, in the particular case of this paper, one can use distinct methods such as the full factorial design, the Taguchi method, the multifactorial method, the response surface designs etc.

In most research presentations, full factorial design is preferred, so that one may calculate the effects of various factors on the process results. By applying this method (full factorial design), one cannot establish if a factor has several levels of variation and the interaction of distinct factors and, for this reason, the number of required experimental tests is very high. The answer to such a problem and especially the reducing of the number of experimental tests could be given by the so called split planes method, which allows modelling experiments far fewer than the full factorial method plan is able to do. The Taguchi method is one of these methods and it has the advantage that it is easy to put it into practice. The Taguchi designs use orthogonal arrays, which estimate the effects of factors on the mean response and variation [1, 11]. Although there are distinct methods of planning the experiment, the use of the Taguchi method was gradually imposed however and it proved to be more effective in comparison with other methods. The objective of the present paper is to emphasize the influence exerted by the process input factors on the weld width, in case of electron beam welding and to emphasize the benefits of use of the Taguchi method.

2. THEORETICAL CONSIDERATIONS

Electron beam welding belongs to the group of nonconventional welding techniques, characterized by multiple advantages over conventional processes, at least for certain practical situations. This process in which the energy transfer causes local heating, followed by melting and vaporization of the workpiece material, is used in many applications in the automotive industry. One can mention as application the welding of sprockets (for which the specialty literature identifies more than 1000 existing equipments), the Diesel engines pistons, clutches, satellite-holder shafts, gears, spark plugs, shock absorbers etc.), aeronautics (the jet rotors and steel structures for aircrafts), nuclear field (workpieces of zirconium alloys, nickel, aluminium fuel rods, sources nuclide generators etc.), microtechnology field (distinct relays, membranes, sensors etc.). The high concentration of the energy specific to the electron beam process leads, in the case of the welding process, to the transfer of energy from the heat source to the workpiece, on the entire thickness of the weld and, as a result, one can observe the introduction of significantly lower heat than in the case of conventional fusion welding processes (Figure 2).

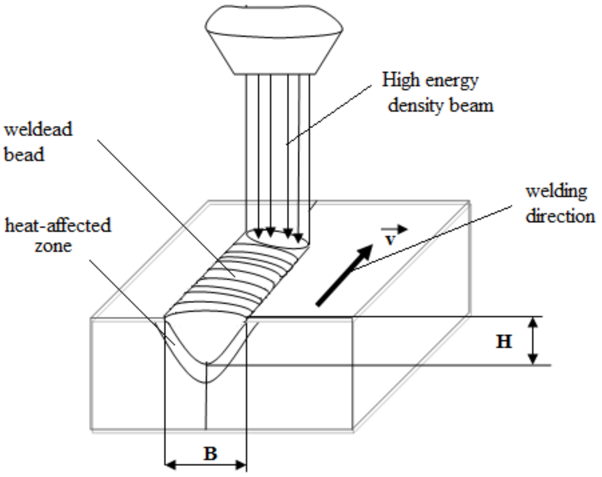

Figure 2. Graphical representation of welding process

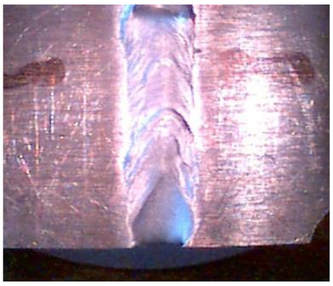

Figure 3. Example of weld achieved by means of electron beam

The small volume of the welding bath (figure 3.) and the possibility of accurate control of electron beam intensity ensure the condition that the negative metallurgical effects (limited to an area with a width of about 1 ÷ 2 times the width of the weld) are less significant than those corresponding to the conventional welding. The cooling rate of the weld is very high, due to the high temperature gradient.

The quality of the joints depends on a great number of parameters, both of the workpiece material and the beam. The main output parameters in electron beam welding are the penetration depth (*H*) and weld width (*B*) depending on various factors such as the beam power (by beam current and acceleration voltage), the welding velocity, the position of the electron focus towards the welded material surface, the vacuum pressure, the welded material etc. A synthetic representation of those factors able to affect the weld width is presented in figure 4.

The welding bead is characterised (in a synthetic characterisation) by the main parameters as welding speed, the intensity or the electron beam current, the current focus etc. and these parameters depends essentially on the capabilities of the welding equipment.

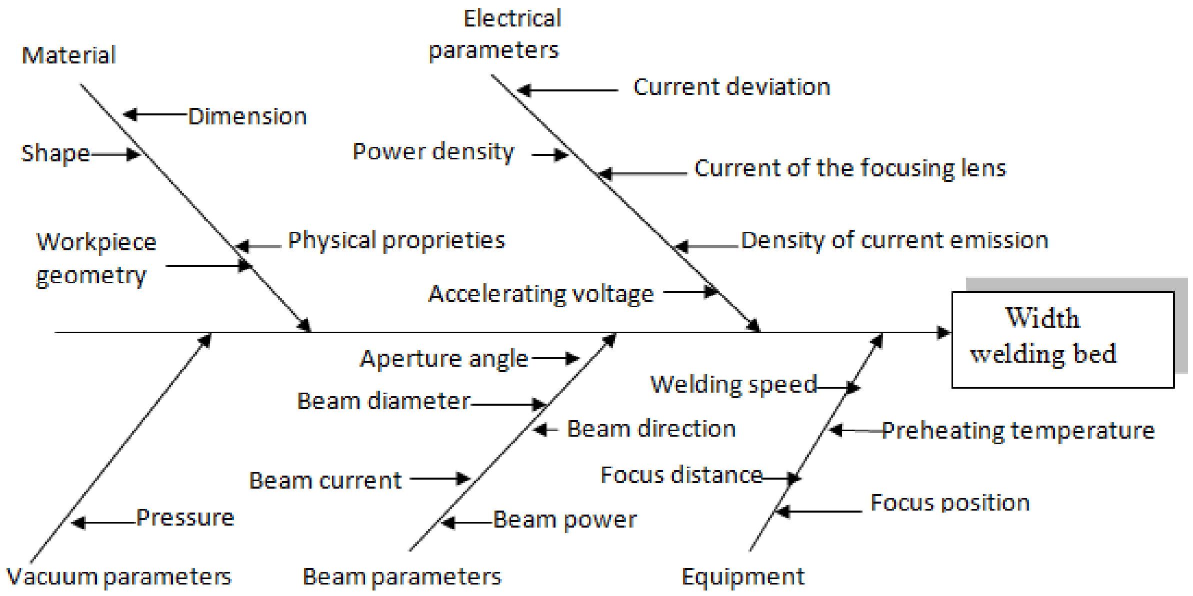

Figure 4. Input factors able to exert influence on the weld width at electron beam welding

3. EXPERIMENTAL RESEARCH

The equipment used within the experiments is an equipment of electron beam welding type ELA 60/60 (AFE), equipped with a vacuum and work chamber. The main technical characteristics of the electron beam welding equipment are the following: accelerating voltage: 60 kV, welding current between 5 to 1000 mA, current focus 400-1000 MA, pressure in the electron gun: $10.7 \cdot 10^{-3}$ Pa ($8 * 10^{-5}$ mm Hg). The enclosure of the working chamber and respectively of the electronic gun is done separately. The gun is evacuated using a preliminary vacuum pump and another one of diffusion and a vacuum chamber for welding; other two preliminary vacuum diffusion pumps are also included in the equipment. The high specific power and specific mode of energy transfer of the electron beam to the workpiece surface layer determine the weld geometry and feature.

According to the Taguchi method applied in order to study the influence exerted by the beam parameters and the welding parameters on electron beam weld width, one must find a fractionated factorial plan, able to determine the model coefficients. Levels of input variation factors are determined after some preliminary tests.

In this research, samples made of carbon steel (S235JR - SR EN 10025-2) were used. The materials were selected by taking into consideration that the carbon steels are most common materials used in various fields and particularly in machine building.

In accordance with the information existing in the specialty literature, the low carbon steels (C <0.3%) have a good behaviour in welding processes; they can be welded by means of electron beam without preheating or post-welding heat treatment.

Table 1. Taguchi plan for the establishing the influence of various factors on the weld width

No.	Parameters						Weld width, mm	
	I_f [mA]		*v* [m/min]		*F* [mA]		Experimental	Theoretical
	level	value	level	value	level	value		
1.	1	150	1	0,23	2	744	12	11,5
2.	2	250	1	0,23	2	744	16	12,85
3.	1	150	2	0,75	2	744	8	8
4.	2	250	2	0,75	2	744	5,7	9,35
5.	1	150	1	0,23	1	714	6	8,75
6.	2	250	1	0,23	1	714	9,2	10,1
7.	1	150	2	0,75	1	714	7,5	5,25
8.	2	250	2	0,75	1	714	8	6,6
Mean value	M		M^t	Sr		Sr^2	**9.05**	**9,05**

4. EXPERIMENTAL ANALYSIS

In order to achieve an adequate mathematical model for the electron beam welding, it is necessary to process the experimental data. An appropriate model depends largely on the conclusions reached in this stage. The establishing of an empirical mathematical model requires two major stages. In the first stage, known as preliminary experiment, one can solves a number of problems concerning the selection of the influence factors and of the main interactions between them, and in the second stage (basic experiment), one addresses a proper development of the model and of its statistical analysis.

In practice, in order to increase the measurement accuracy, an experiment is repeated under identical conditions, but the measured values did not remain strictly at the same values. Sometimes differences in the values of the measured sizes appear because, in reality, one can maintain as constant values only a limited number of factors that are able to act in the system. The full factorial plan consists in addressing all possible combinations of the factors taken into account during the experimental tests. The main objective of a Taguchi experimental plan is to reduce the number of experiences for the system behaviour ascertains, but without losing the precision observations.In the case of weld width, there were established the input factors and their variation levels according to information found in the specialty literature. In the experimental tests, the results of the preliminary tests were taken into account in establishing the input factors, in setting the variation levels for each factor and on the base of the technological possibilities of the equipment for electron beam welding.The factors that could affect the system response and which depend on the welding equipment characteristics are: intensity (current) of electron beam (I_f), welding speed (v), focus current (F) and interaction between the speed welding and the current intensity. The factors which could be constantly maintained are the acceleration voltage (U_a), the electronic cannon pressure (P_{te}), the vacuum chamber pressure (P_i) and the shooting distance (d_l). In accordance with this succinct analysis, the factors affected by changes during the welding process were: the cutting speed, v [m / min], the current intensity I_f [mA] and the focus current F [mA].

In order to analyse, to interpret and to validate the results regarding the above mentioned influences, the followed steps of using the Taguchi method were performed:

- The establishing of the input parameters and of the output parameters. With this aim in view, all the information already known was collected and, in addition, some assumptions that may be made were identified (the presence of interactions between the factors, the existence or non-linear effects etc.);
- The check of the orthogonality by building the panel of incidents with dual input, thus being possible to precisely define the research objective, the number of factors that could be analysed (the interactions between factors determining the sufficiency or insufficiency of only linear influences etc.);
- The selection of the Taguchi table, establishing the set of experiences necessary to be taken into consideration so that the research objectives are fulfilled;
- The elaboration of the graphic representation corresponding to the proposed model;
- The elaboration of the matrix model;
- The design of experimental research table and achieving the planned set of experiments;
- The calculation of the impact factors;
- The elaboration of the graphic representations of averaged effects;
- The elaboration of the matrix model corresponding to the system and developing its analysis (analysis of variance, finding a position of dependence, optimization etc.).

After the acquisition of the experimental data, in accordance with the Taguchi experimental method requests, the calculation of the impact for some factors and elaboration of the graphical representations of the calculated average effects, were achieved. The results could lead to the following conclusions:

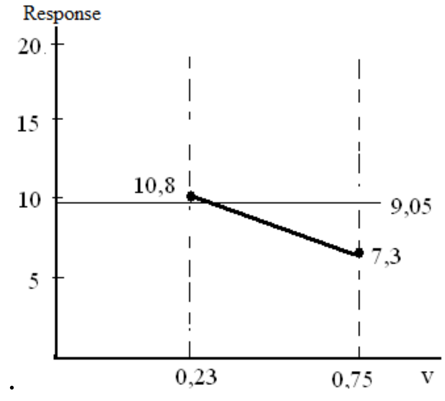

Figure 5. The effect of the factor *v*

- I_F factor is able to increase the width of the weld (negative response system);

- The factors v and F have a great influence and lead to decrease of the weld width, as a consequence of the transition of the factors from level 1 to level 2;

- The factor *v* has the greatest influence (slope being the highest, as one can see in figure 5) and determine a decrease of the weld width, during the transition of the factor from level 1 to level 2; thus, one can consider that *v* is the main influence factor.

The system matrix model, which expresses the effects of factors (electron beam current (I_f), welding speed (v), the focus current (F) on the weld width (B) can be written as in equation (1) :

$$B^t = 9{,}05 + [\mathbf{-0,675} \quad 0{,}675]\, I_f + [1{,}75 \quad \mathbf{-1,75}]v + [1{,}375 \quad \mathbf{-1,375}]F + I_f^t \begin{vmatrix} -2{,}475 & \mathbf{-2,225} \\ +2{,}475 & 0{,}225 \end{vmatrix} v (1)$$

If one takes into account the influence of the input factors that can be modified, the optimization of the system response involves finding the minimum of all possible answers (the smallest weld width value). From the studied model, but also from graphics, one can conclude that, in order to obtain the smallest weld width by electron beam welding, the influence factors can be used as following: the intensity of the electron beam current on level 1 (I_f = 150 mA), the welding speed at level 2 (v = 0.75 m / min), and the focusing current on the level 2 (F = 714 mA). The graph shows that the favourable effect of the interaction of I_f and v will be reached when I_f is on the level 1 and v on the level 2. The values written with bold fonts (in the matrix model) are the ones that should be used to find the minimum sought.

5. CONCLUSIONS

Considering the intention to improve the knowledge base related to the weld width, in case of the electron beam welding of distinct materials, this paper presents a series of experimental research conducted by the author and the results of such research. The research goal took into considerations the current knowledge in this area and also the data relating to the applicability of the results and the available workpiece materials.

In order to reduce the total number of experiments and to diminish the duration of their processing, without lowering the reliability of results, the principles of the Taguchi experimental planning method was used.

This method was preferred to be applied instead of the traditional methods due to possibility to study inclusively the interactions between some of the input factors involved in process.

Applying the Taguchi experimental planning method allowed the development of a statistical analysis of results (analysis of variance, finding a position of dependence, optimization etc.) and the interpretation and validation of experimental results.

6. REFERENCES

1. Benoist, D., *Notions sur les plans d experiences.* Edition Technip. Available at: http://books.google.com/books?hl=ro&lr=&id=yiHjQlbN8A8C&oi=fnd&pg=PA9&ots=Q-I28Dz8Xx&sig=S6sb2Srs9xV23kuiqC8S7wRlQew#PPA10,M1, Accessed 15 April 2014
2. Creţu, G., *Basics of experimental research* (in Romanian), Technical University “Gh. Asachi” Editing House, Iasi, Romania, (1998).
3. Dey, V., Pratihar D. K., Datta G.L. , Jha M.N. , Saha,T. K. , Bapat A.V., Optimization of bead geometry in electron beam welding using a genetic algorithm, *Journal of Materials Processing Technology,* Vol. 209, No. 3, (2009).
4. Dulău, M., David, L., Şoaită, D., *Mathematical Models for Thermal Source used in Electron Beam Processing, Optimum Technologies, Technologic Systems and Materials in the Machines Building Field*, TSTM 6 - Romanian Academy, Branch Office of Iaşi, (2000).
5. Goupy J. L. Etude comparative de divers plans d experiences. *Revue de statistique appliquée,* Vol. 38, No. 4, (1990).
6. Friedel, K.P., Felba, J., Pobol, I., Wymysłowski, A., A systematic method for optimizing the electron beam hardening process, *Vacuum,* Vol. 47, No. 11, pp. 1317–1324, (1996).
7. Koleva, E. Electron beam weld parameters and thermal efficiency improvement, *Vacuum, Vol.* 77, pp. 413-421, (2005). Available at: www.elsevier.com/locate/vacuum. Accessed: 23.11.2014.
8. Petrov, P., Sabchevski, S. Parameters used for electron beam welding – A comparative study, *8th International Conference on Beam Technology,* Sofia, Bulgaria, (2010).
9. Palmer, T. A., Elmer, J. W., Nicklas, K. D., Mustaleski, T., Transferring Electron Beam Welding Parameters Using the Enhanced Modified Faraday Cup, *Welding Journal*, Vol. 86, (2007).
10. Rouquette, S., Guo, J., LeMasson, P., Estimation of the parameters of a Gaussian heat source by the Levenberg–Marquardt method: Application to the electron beam welding, *International Journal of Thermal Sciences*, Vol. 46, No. 2, (2007).
11. Introduction to Taguchi method. Available at: http://www.ecs.umass.edu/mie/labs/mda/fea/sankar/chap2.html. Accessed: 22.05.2015.