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SOME CHARACTERISTICS OF ELECTRON BEAM MELTING PROCESS

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Abstract: *The electron beam melting is a process applied in case of some electron beam machining methods. Essentially, the electron beam machining is based on the effects generated in the workpiece surface layers as a consequence of the penetration in this layer of electrons included in a high energy electron beam. For this reason, it is important to better know the characteristics of the melting processes developed in the workpiece material under the action of high energy electron beam. The method of systemic analysis was applied in order to highlight the factors able to exert influence on the output parameters specific to the electron beam melting process. A complete factorial experiment was thought and developed; by mathematical processing of experimental results, empirical models being determined. The analysis of empirical mathematical models and some graphical representations elaborated on the base of these empirical models allowed formulating some remarks concerning the variation of the weld depth and width at the variation of electron beam current intensity and speed of relative motion between electron beam and test piece.*

Key words: *electron beam melting, systemic analysis, beam current intensity, relative motion speed, empirical models.*

1. INTRODUCTION

Generally, the name of *nonconventional* or *nontraditional* is attributed to a machining method or technique when it presents characteristics distinct in comparison with the known machining methods or techniques.

However, in the field of machining methods, there is the opinion to use the concept of *nonconventional machining methods* in the case when these machining methods involves a supplementary transfer of energy to the machining zone [4, 9], so that either a classical machining method develops in better conditions or a machining method based on other phenomena than the plastic deformation (which is considered as phenomenon found at the base of so-called *classical machining methods*, where techniques such as cutting – turning, milling, drilling, grinding etc. are included – or sheet machining, from which machining methods such as punching, drawing etc. are taken into consideration to be included) are applied; such other phenomena are electrical discharges, chemical reactions, heating by means of plasma beam, laser beam, electron beam etc.

Usually, these nonconventional machining technologies are applied when the workpiece material is too hard to be machined in conditions acceptable for the producer or even the machinability by classical machining methods of the workpiece material is so low, that really the classical machining methods cannot be applied, in order to obtain certain surfaces of the part. Another case when nonconventional machining methods are applied corresponds to the situation when the part to be obtained has complex surfaces, difficult or even impossible to be obtained by classical machining methods.

In such situations, a research concerning the possibilities to apply some of nonconventional machining methods could be developed. If the phenomena found at the base of nonconventional machining methods is considered, one can notice that these phenomena could be mechanical, physical (heating) and chemical.

If the existence of a proper tool is taken into consideration, one can notice that there are nonconventional machining methods which use a materialized tool and nonconventional machining methods where there is not a solid body having the roll of the tool. In the last group, the so called *electron beam machining* is included.

This machining method – electron beam machining – is based on the physical and chemical effects generated at the contact with the surface of the workpiece by a beam of electrons accelerated and directed to certain zones of the workpiece.

The most applied electron beam machining methods are based on heating of the workpiece material up to temperatures when this material is melted or even vaporized, but there are also electron beam machining methods when chemical reactions are developed under the action of the electron beam, just in the workpiece material or between certain distinct substances which constitute the workpiece material. Since the electron beam machining methods develop usually in a vacuum medium, up to

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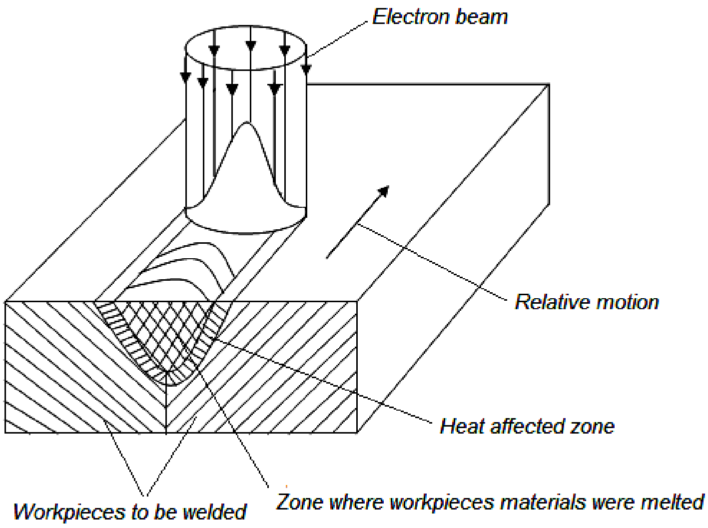

Fig. 1. Developing of welding process.

now there are not known machining methods in which the workpiece material could react with the environment found in contact with the workpiece material, so as some chemical reactions develop in the case of other nonconventional machining methods (electrical discharge alloying, laser beam alloying, plasma beam alloying etc.).

If the mass changes during the electron beam machining are considered, one can notice that there are *subtractive machining methods*, where there is a material removal from workpiece, *additive machining methods*, in which the workpiece mass increases as a consequence of applying an electron beam machining method and, on the other hand, there are *electron beam machining methods when the mass of the workpiece does not significantly change* (for example, this is the case of electronoresist exposure, within e more complex chemical machining methods).

Among the additive electron beam machining method, one can meet the electron beam welding; this manufacturing method involves the melting of the materials to be welded by means of the heat generated in the contact zone of workpieces by means of a high energy electron beam.

The first knowledge concerning the possibility to use the electron beam in order to develop a manufacturing process was suggested in the first half of the twenty century, by the German researchers Manfred von Ardenne and Rudolf Kuhle; they proposed to use the electron beam applied in electron beam microscopy in order to develop some subtractive machining methods, by using the vaporizing of the workpiece material, under the action of an intense electron beam.

The electron beam seems to be applied first time in order to develop a welding process by J. A. Stohr, who defended a doctoral thesis and published results concerning electron beam welding in the in the fifties of the last century.

The electron beam melting was used by Rännar et al. in order to obtain free-form cooling channels by the direct-metal rapid tooling method using the electron beam melting [7]. They showed that in this way some advantages concerning cooling time and dimensional accuracy could be ensured just by applying the electron beam melting.

Zäh and Lutzmann noticed that within the additive manufacturing technology, the use of laser beam seems to be limited, due to the inertial beam deflection device and a solution to improve this situation could be the use of electron beam. They developed a thermal model on the base of finite element method and developed experimental researches finalized by elaboration of so-called process window, by taking into consideration the influence exerted on the melting process by the scan speed and beam power [10].

Rafi et al. developed a comparison of the selective laser melting and electron beam melting, by considering the microstructure and some mechanical properties of Ti6Al4V parts produced by the two melting processes and explained the noticed differences by the distinct cooling rates [6].

Ammer et al. used a three dimensional thermal lattice Boltzmann method in order to simulate the melting process generated under the action of electron beam. They offered adequate explanations based on taking into consideration the absorption rate and the energy dissipation [1]. The validation of the established model was made by the comparison of analytical and numerical solutions of the heat equation.

Scharowsky et al. used a high speed camera and an illumination laser in order to better observe the melting process and obtained information characterized by higher resolution about the spatial and temporal evolution of the process [8**].**

In Romania, ample researches concerning the use of electron beam in order to materialize machining processes were developed within doctoral activities by Zeno Pircea (doctoral thesis defended in 1982), Eugen Tătar (1982), Anghel Tăroată (1990), Ovidiu Tătaru (1995), Dumitru Neagu (1999) [5], Adriana Munteanu [3].

2. THEORETICAL CONSIDERATIONS CONCERNING ELECTRON BEAM MELTING

As above mentioned, the electron beam welding uses the heat developed in the contact zone between two workpieces to melt their material and to achieve thus welding seams, for example. It could be interesting, from this point of view, to have deeper knowledge concerning the phenomena which develop in the zone affected by the action of the high energy electron beam.

Essentially, the electron beam is achieved by means of an electronic tube, as a consequence of the high voltage applied between the thermocathode and a perforated anode; focusing deflection coils direct the electron beam to the contact zone between workpieces. The process develops in a vacuum work chamber, in order to avoid the energy waste by collision of electrons with gas molecules and the possible contamination of molten metallic material by these gas molecules. Due to low dimensions of electrons, they could penetrate the workpiece surface layer, passing between the metallic ions placed in the crystalline net nodes. Subsequently, the electrons trajectory and speeds could be affected by the collisions with or by influence exerted by metallic ions, to whom a part of electrons kinetic energy is transferred.

It is known that as particles found in motion, the electrons have the kinetic energy W_k defined by the relation:

$$W_k = \frac{m_e v_e^2}{2}, \quad (1)$$

where m_e is the electron mass ($m_e = 9.1066 \cdot 10^{-28}$ g) and v_e is the electron speed.

The electron speed v could be estimated [4, 8] if the voltage U applied to electrodes and the electric charge e of the electron ($e = 1.602 \cdot 10^{-19}$ As) are known:

$$v = \sqrt{\frac{2eU}{m}}. \quad (2)$$

The thickness of the layer initially penetrated by the electron beam layer could be estimated [4, 8] by means of the relation:

$$\delta = 2.2 \cdot 10^{-12} \frac{U^2}{\rho}, \quad (3)$$

where ρ is the material density, in g/cm^2.

Taking into consideration a voltage U = 5 000–60 000 V and the density ρ =7.8 g/cm^3 valid in case of iron, one can notice that $\delta = 7.1 \cdot 10^{-6} - 0.001015$ cm.

In zones placed at depth higher then δ, the electrons transfer their energy to the ions whose vibration amplitude increases and this means that the local temperature increases fast, due to the thermal source thus appeared.

A part of the electrons are probably reflected by the workpieces surfaces and only the electrons which penetrated in the workpiece surface layer will transfer their kinetic energy to the workpieces materials, generating a heating phenomenon. Not all the thermal energy is used for materials melting; a part of thermal energy is dissipated in the workpiece material by conduction. Finally, one can consider that only a part k of the electrons kinetic energy is used for materializing the melting phenomenon:

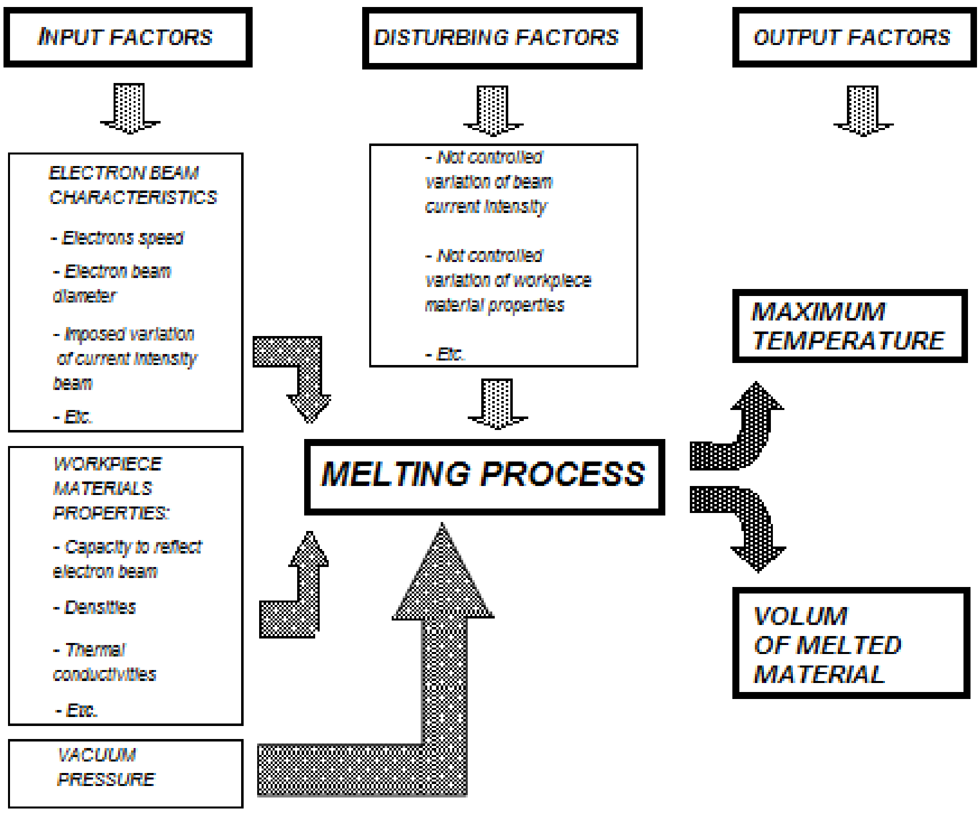

Fig. 2. Graphical representation corresponding to the systemic analysis of electron beam melting process.

$$W_k = k\frac{m_e v_e^{\,2}}{2}. \qquad (4)$$

The volume of the material melted under the action of electron beam is dependent on many factors; a systemic analysis could be developed in order to highlight the main factors able to affect the melting process (Fig. 2).

One can appreciate that two groups of *input factors* could affect the melting process:

a) *Electron beam characteristics;* electrons speed, electron beam diameter and imposed variation of current intensity in electron beam could be included here;

b) *Workpieces materials properties* (capacity of the workpiece surface to reflect the electron beam, materials densities, materials thermal conductivities etc.);

c) *Pressure* corresponding to vacuum.

As *output parameters*, one took into consideration the maximum temperature reached by materials and this temperature must exceed the melting temperatures of the workpieces materials eventually found in contact and volumes of materials which are melted, respectively. At the same time, the temperature has to not exceed the vaporizing temperature, in order to avoid generation of microexplosions, by sudden increase of the workpieces materials volumes; such an increase could significantly affect the welds quality.

Some of *the disturbing parameters* could be the non controlled variation of the current intensity beam and of the workpiece materials properties, if one accepts a possible inhomogeneity of these materials.

3. EXPERIMENTAL RESEARCH

Some experimental researches were designed and developed in order to highlight the influence exerted by the input factors on the dimensions of zone affected by melting process. One considered the depth *H* and the width *B* of the weld.

An equipment for electron beam welding (ELA 60/60 –AFE) existing in the National Research and Development Institute for Welding and Material Testing of Timişoara was used in order to estimate effect exerted by the electron beam on the test piece made of high speed steel HS18-4-1. The equipment is able to ensure a maximum acceleration voltage U = 60 kV; the welding current can be changed in the interval 5-1000 mA. The vacuum pressure is of $10.7\cdot10^{-3}$ Pa.

The steel HS 18-4-1 includes 0.72 % carbon, 17.257 % tungsten, 3.87 % chromium, 0.92 % vanadium, 0.169 % molybdenum, 0.127 % copper. The test pieces were cut by means of a water jet cutting equipment existing also in the National Research and Development Institute for Welding and Material Testing of Timişoara. The surfaces placed perpendicularly on the weld were subsequently polished and a metallographic reactive (Nital) was applied for highlighting the structure of these surfaces. A Carl Zeiss Jena digital microscope was used to study the surfaces at magnifications changeable from 100× to 600×.

As independent variable during the machining process, one used the beam current intensity I_b (30–50 mA) and the machining speed v (0.2–0.8 m/min).

The experimental results were inscribed in Table 1.

A specialized software [2] based on the use of the method of least squares was applied in order to mathematically process the experimental results. The software allows evaluating the adequacy of the determined empirical models by means of the so-called Gauss's criterion; this criterion takes into consideration the sum of squares corresponding to differences between the values measured and the values allocated on the basis of proposed function, for the same experimental points.

By using the above mentioned software, the following empirical mathematical relations were determined:

$$h = 19.747\text{-}0.879 I_b + 0.0134 I_b^{\,2} - 5.0v + 0.000235v, \qquad (5)$$

for which the Gauss's criterion has the value S_G=0.5318182, and

$$b = -3.698 + 0.389\cdot I_b - 0.00399\cdot I_b^{\,2} - 6.25\cdot v + 1.25\cdot v^2, \qquad (6)$$

in this case the Gauss's criterion having the value $S_G = 2.184069\cdot 10^{-9}$.

Since within the manufacturing processes frequently power type functions are preferred, by means of the same software the following mathematical relations were also established:

$$h = 0.004425\cdot I_b^{\,1.721}\cdot v^{-0.579}, \qquad (7)$$

the Gauss's criterion having the value S_G=1.503082 and

Table 1

Experimental results

Beam current intensity I_b, mA	**Machining speed v, m/min**	**Depth of weld, h, mm**	**Width of weld, b, mm**
30	0.2	4.10	3.2
30	0.4	3.7	2.1
30	0.6	2.8	1.1
30	0.8	1.4	0.2
40	0.2	5.5	4.3
40	0.4	5.1	3.2
40	0.6	1.2	2.2
40	0.8	2.8	1.3
50	0.2	8.1	4.6
50	0.4	7.7	3.5
50	0.6	6.8	2.5
50	0.8	5.4	1.6

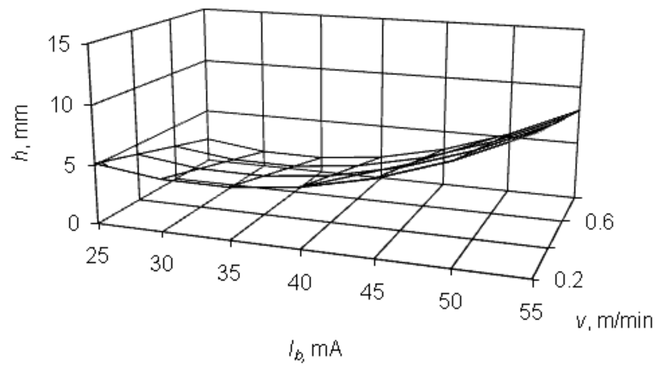

Fig. 3. Influence exerted by the beam current intensity I_b and machining speed v on the depth of weld h .

$$b = 0.000777 \cdot I_b^{1.894} \cdot v^{-1.102}, \qquad (8)$$

for which the Gauss's criterion is S_G = 1.059839.

Even the power type function is not the most adequate model, it facilitates the obtaining a general image concerning the influence exerted by the independent variables on the output parameters by analyzing the values of the exponents attached to the independent variables in the empirical models.

On the bases of the relations (7) and (8), the graphical representations from figures 3 and 4 were elaborated.

The analysis of the mathematical empirical relations (7) and (8) and of the graphical representations allows formulating some remarks.

Thus, in accordance with the diagram from figure 3, the depth of weld h has a minimum for a low value of the beam current intensity I_b and afterwards it is affected by an increase, as expected. At the same time, the depth h of weld decreases when the machining speed v increases in the interval 0.2 – 0.8 m/min; the fact could be explained by the short duration of action exerted by the electron beam on the test piece, in case of higher value of machining speed v.

The graphical representation from figure 4 highlights a maximum of the weld width b when the beam current intensity I_b increases, but the increase of the weld width b is more pronounced at the increase of beam current intensity I_b. As expected, the decrease of the weld depth b could be highlighted at the increase of machining speed v and the explanation shown in the case of the variation of the weld depth h could be considered as valid also in this case.

4. CONCLUSIONS

One of the nonconventional machining methods based on the effects generated at the contact with workpiece material of a high energy electron beam is the electron beam machining. Among the larger group of electron beam machining methods, there are some techniques which take into consideration the melting phenomena; for example, such a phenomenon has an important role in the welding processes. The study of the specialty literature highlighted the existence of many research preoccupations directed to the better knowledge of aspects specific to the melting processes developed in workpieces surface layers under the action of high energy electron beam. In order to highlight the influence exerted by some input factors on the output parameters of electron beam melting process, a systemic analysis was thought and elaborated. Some theoretical considerations facilitated a better highlighting of the temperature increase as a consequence of electrons penetration in the workpiece material. An experimental research based on a design of complete factorial experiment by using three input factors at two levels was thought and materialized. In this way, some empirical mathematical models were established by mathematical processing of experimental

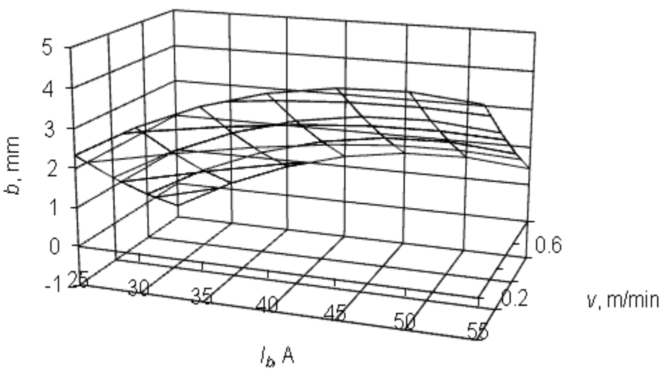

Fig. 4. Influence exerted by the beam current intensity I_b and machining speed v on the width of weld b.

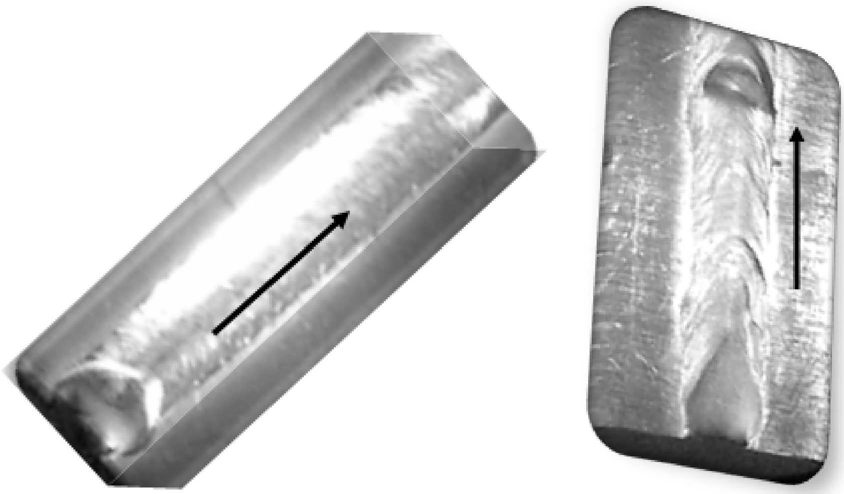

Fig. 5. Aspects of surfaces obtained by electron beam melting.

results. One preferred the power type functions as empirical models due to the fact that the sizes of exponents attached to each independent variable offer a more direct image concerning the influence exerted by the input factors on the depth and width of melted zone. The empirical mathematical models and the graphical representations achieved on the base of empirical models allowed formulating some observations concerning the evolution of the output parameters at the variation of the electron beam current intensity and motion speed.

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