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Electron Beam-Based Rapid Prototyping - State of the Art

Abstract: Fast prototyping involving the use of an electron beam and a deposited material in the form of a wire is an efficient method enabling the making of elements having complicated shapes and made of expensive technical alloys, e.g. alloy steels, nickel or titanium alloys. The demand for fast prototyping results from the development of new technologies in the automotive, aviation and machine-building industries. The article discusses the advantages of fast prototyping methods confronted with conventional prototyping methods as well as presents ideas behind the fast prototyping and primary process parameters. The fast prototyping technology involving the use of a wire and an electron beam as the source of energy should gain recognition among Polish entrepreneurs intended to implement innovative solutions in their companies.

Keywords: electron beam, rapid prototyping, fast prototyping

Introduction

With growing market competition, the rapid prototyping of metallic materials involving the use of a wire makes it possible to reduce time necessary for the making of a functional prototype [1]. Commonly used CAD/CAM systems only enable the preparation of virtual models. As regards welding technologies, three groups of methods can be used for the rapid making of metallic elements. The three aforementioned technologies utilise the following sources of heat:
a) welding electric arc (WAAM – wire arc additive manufacturing),
b) laser beam (WLAM – wire laser additive manufacturing),
c) electron beam (EBAM – electron beam additive manufacturing).

The thickness of a single layer and the rate of deposition in the wire-based rapid prototyping are significantly greater in comparison with powder-based prototyping methods. Figure 1 presents the comparison of deposition methods involving the use of powder with those utilising a wire.
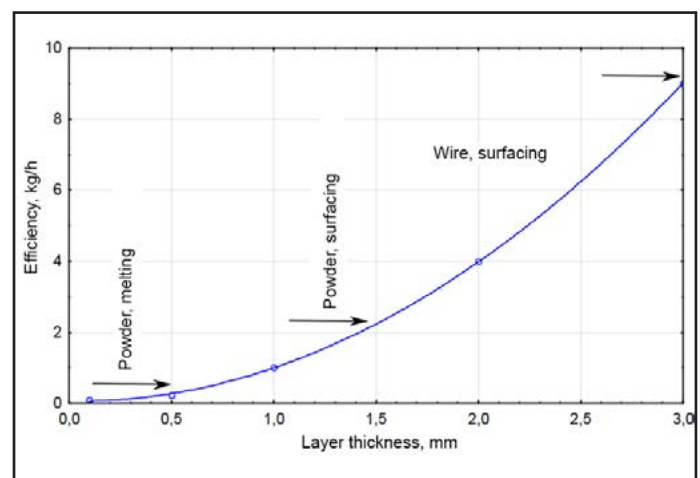

Fig. 1. Comparison of the efficiency and the thickness of a single layer obtained using powder and wire-based deposition technologies

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The dimensional accuracy of elements made using a wire is lower than that of products made using powder-based technologies. In addition, the surface coarseness of the former is higher. In turn, methods involving the deposition of a wire provide higher process efficiency.

The most commonly used rapid prototyping methods involving the use of a wire and welding electric arc include TIG, MIG/MAG and plasma surfacing. Laser wire rapid prototyping can be performed using both CO_2 lasers and solid-state lasers.

The initial stages of product development generate the most important components concerned with product manufacturing costs and related to the function, design, materials and production technology. The essential stages concerning the development of a new product usually result in the making of a prototype, which, as early as during the product development

Table 1. Comparison of rapid prototyping processes with conventional technologies [5]

Aspect	Rapid prototyping	Conventional technologies
Cost	Elements can be made at a relatively low expense, yet primarily in cases of small and medium lots, rarely in mass production.	Because of costs connected with, e.g. casting moulds, forging tools etc., conventional methods usually prove expensive in terms of piece production and low-volume production.
Time	Time necessary for making a single element can be very short. Elements are made directly from a CAD model. Such a solution makes it possible to save time necessary for delivering end products through limiting the stage of production development, reducing the supply chain and becoming independent of stock.	In general, time necessary for making elements is very long and depends on the availability of moulds, dices, tools etc.
Consumption of materials	Only the optimum amount necessary for the making of an end product.	Very high.
Product complexity	Elements can be highly complicated. The final shape is primarily limited by the designer's imagination.	The production of geometrically complex elements is restricted. Numerous parts must be made separately and joined afterwards.
Quality and applications of products	The quality of an end product depends on applied technology. Initially, parts made using the rapid prototyping methods were not applied as elements of critical importance intended for operation under considerable loads. However, the fast development of rapid prototyping technologies translated into the enhanced quality of products, enabling their use as load-bearing elements.	Because of their very high quality, products are used in load-bearing structures.
Waste	A limited amount of waste material, particularly as regards machines provided with a wire feeding system (compared with techniques utilising powder).	A significant amount of waste material.
Prototyping	High usability when prototyping and assessing concepts of products. Possible changes in the design and appropriate feedback.	Conventional technologies are not popular when making prototypes and assessing concepts of products. Highly expensive and time-consuming production of single elements.
Process qualification and product certification	In terms of practicality, the certification of processes is more problematic in comparison with that concerning conventional methods. As the above-named technologies are new on the market, the availability of related standards is very limited.	Conventional production technologies are mature, offering many available standards and procedures.

stage, enable the first visual, functional and, sometimes, even market-related assessment of product features. Prototyping based on conventional methods is both lengthy and costly as traditional methods require a significant amount of manual labour performed by highly skilled workers. In addition, a model made manually disrupts the cycle of electronic information circulation between the design level and the level of production proper [2]. Rapid prototyping technologies are also useful when making spare parts and short or medium lots, in relation to which the use of forging or casting processes is unprofitable.

Although in many cases the rapid prototyping of metallic elements involving the use of a wire will not replace already existing processes, it can reduce manufacturing costs, particularly in cases of expensive titanium or nickel alloys. In addition, additive technologies facilitate the design and the making of elements having complicated shapes, e.g. in the aviation and/or aerospace industries [3]. Table 1 presents conventional manufacturing processes (e.g. rolling, forging or casting) compared with rapid prototyping processes. The size of the rapid prototyping machinery and services-related market is estimated at 3.7 billion euro, i.e. 2% of the entire equipment and machinery market. The estimated size of the market is expected to reach 9.4 billion euro in 2020 [4].

Electron Beam Rapid Prototyping

In the process of electron beam rapid prototyping involving the use of a filler metal wire, the filler (deposited) material (metal) is supplied to the liquid metal pool continuously provided with energy of the concentrated electron beam generated by the electron gun (Fig. 2). The bombardment of the filler metal deposition area by the strongly focused electron beam having a focus diameter restricted within the range of 0.1 to 0.8 mm is responsible for the transformation of the kinetic energy of electrons into absorbed thermal energy melting the filler metal and base material (substrate) [6-8]. Technologically, the process of rapid prototyping involving the use of a wire (filler metal) can be viewed as selective surfacing. The programing of a CNC machine enables the precise representation (reproduction) of a prefabricated element, whereas state-of-the-art equipment enables the precise adjustment of technological parameters. After being provided with a filler metal wire feeder, a versatile electron beam welding device can be used in the process of rapid prototyping (Fig. 3).

The method of liquid metal transfer in the electron beam deposition process involving the use of a wire differs significantly from the well-known manner observed in arc surfacing performed using, e.g. the MIG/MAG process. In MIG/MAG-based surfacing (and rapid prototyping) molten metal drops are moved from the electrode wire to the liquid metal pool by gravitational force and forces occurring in electric arc. Changes in current parameters of the arc surfacing process (e.g. filler metal wire feeding rate) enable the precise adjustment of the liquid metal transfer. In turn, in cases of electron beam deposition, similar to laser beam deposition, the liquid metal drop is primarily affected by gravitational force, "electron beam force", surface tension force and metal-vapour jet force [9]. The distribution of forces affecting the liquid metal drop during electron beam deposition is presented in Figure 4.
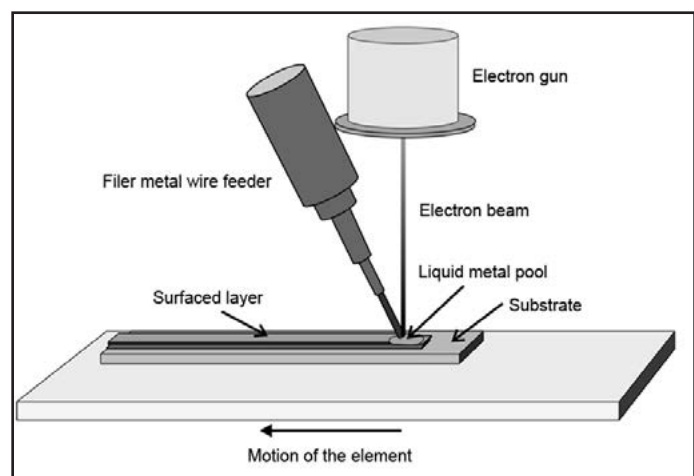

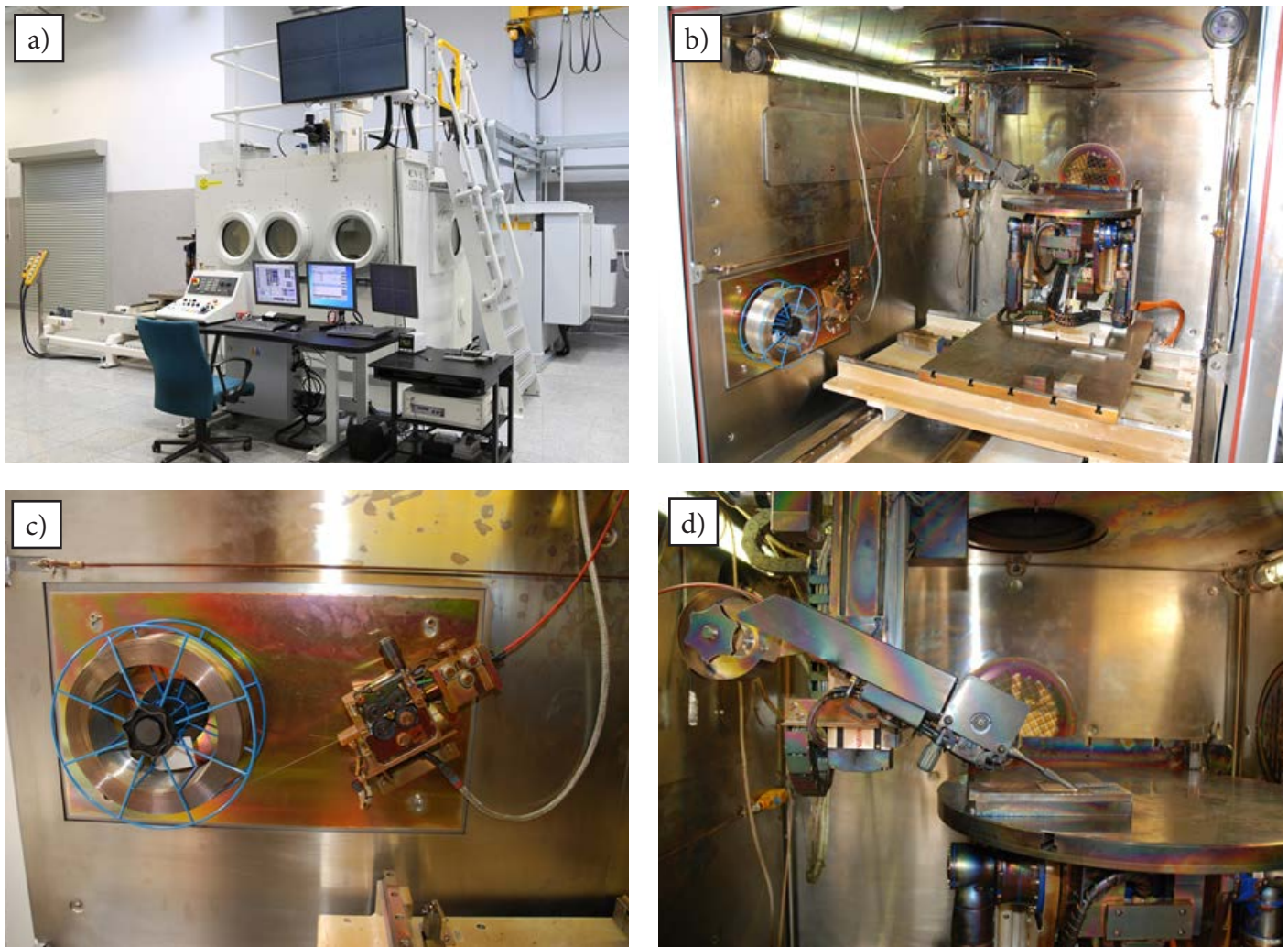Fig. 2. Schematic diagram of electron beam rapid prototyping

Fig. 3. Equipment for electron beam welding and rapid prototyping involving the use of a wire, a) main view, b)-d) elements of the filler metal wire feeding system
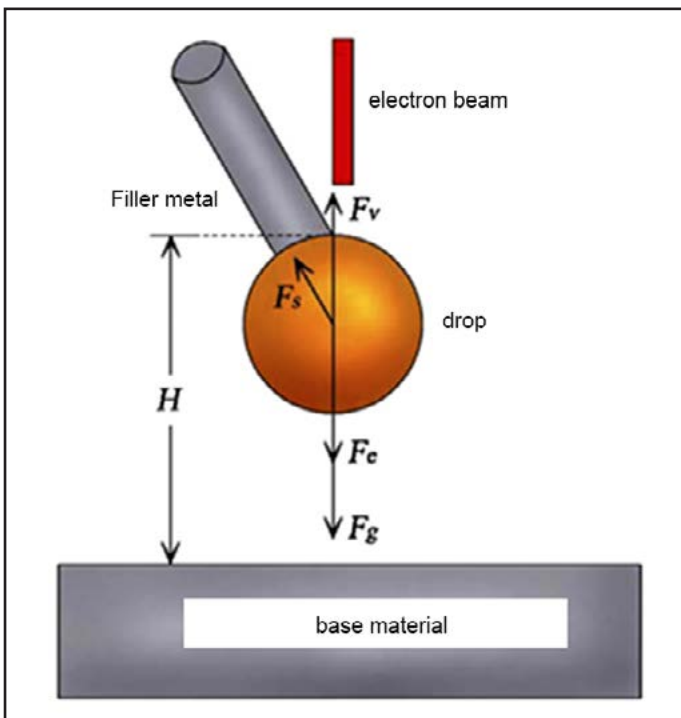

Fig. 4. Forces affecting liquid metal drops [9], H – distance between the tip of the wire and the surface subjected to surfacing, F_g – gravitational force, F_e – electron beam effect force, F_s – surface tension force, F_v – metal-vapour jet force

If the value of forces responsible for drop separation exceeds the value of forces preventing the separation of the liquid metal drop from the tip of the wire, the drop moves to the liquid metal pool. Therefore, the equation of equilibrium can be expressed as follows [9]:

$$F_g+F_e=F_v+F_s \qquad (1),$$

where:
F_g – gravitational force,
F_e – electron beam effect force,
F_s – surface tension force,
F_v –metal-vapour jet force.
Gravitational force F_g can be expressed as follows:

$$F_g=mg \qquad (2),$$

where
m – weight of the drop having the longest diameter,
g – gravitational acceleration.

The weight of the drop can be calculated using the following expression:

$$m = \frac{4}{3}\pi\rho_l r^3 \qquad (3)$$

where:
ρ_l – density of the liquid metal of the drop,
r – critical value of the drop radius.

The source of total energy acting from the outside is the motion of accelerated electrons. For this reason it can be assumed that the above-named energy is equal to the kinetic energy of electrons:

$$F_e\, t = m_t\, v_e \qquad (4)$$

where
m_t – total mass of electrons,
v_e – electron velocity,
t – time unit.

The velocity of electrons can be expressed as follows:

$$v_e = \sqrt{\frac{2UI}{m_t}} \qquad (5)$$

In turn, the mass of electrons can be expressed as follows:

$$m_t = \frac{I}{e}m_e \qquad (6)$$

where:
I – electron beam current,
e – electron charge,
m_e – electron mass.

Metal-vapour jet force P_v is the function of the temperature of the liquid metal surface and can be expressed as follows:

$$P_v = 0{,}54 P_0\, exp\left(\Delta H_{Lv} \frac{T - T_{LV}}{RT\,T_{LV}}\right) \qquad (7)$$

where
P_0 – normal atmospheric pressure,
H_{LV} – latent evaporation heat,
R – universal gas constant,
T_{LV} – boiling point of the base material (substrate),
T – temperature of the liquid metal surface.

The metal-vapour force can be expressed as follows:

$$F_v = P_V\, S \qquad (8),$$

where
S – area from which metal-vapour jet forces act is $S = \pi r_e^2$,
r_e – radius of the circle where metal-vapour jet forces act – electron beam radius.

The force of surface tension can be calculated using the following dependence:

$$F_s = 2\pi r_w\, \sigma_w\, sin\theta \qquad (9),$$

where
r_w – radius of the filler metal (wire),
σ_w – surface tension,
θ – filler metal feeding angle.

Having taken the above-presented dependences into consideration, equation 1 can be expressed in the following manner:

$$\frac{4}{3}g\pi\rho_l r^3 + I\sqrt{\frac{2Um_e}{e}} = 0{,}54 P_0\, exp\left(\Delta H_{Lv} \frac{T - T_{LV}}{RT\,T_{LV}}\right) \cdot$$
$$\cdot\, \pi r_e^2 + 2\pi r_w \sigma_w sin\theta \qquad (10)$$

The previous calculations [9] revealed that the effect of the electron beam force is negligible in comparison with other forces affecting the liquid metal drop. As a result, the critical value of the liquid metal drop can be calculated using the following dependence:

$$(11)$$

$$r = \left(\frac{0{,}405 P_0 r_e^2\, exp\left(\frac{\Delta H_{LV}}{RT_{LV}}\right)}{\rho_l g}\, exp\left(-\frac{\Delta H_{LV}}{RT}\right) + \frac{3 r_w \sigma_w sin\theta}{2\rho_l g}\right)^{1/3}$$

The equation is satisfied if $H \geq 2r$.

Tests performed by J. Zhao [9] revealed that, initially, the deposition process is unstable and can be divided into two stages. The first stage is characterised by the smaller diameter of liquid metal drops being transferred, higher transfer frequency and greater spatter. The second stage is characterised by the movement of greater metal drops, lower transfer frequency and smaller spatter.

In turn, the transfer of a liquid metal drop can be divided into four stages, i.e. an increase in the drop volume, oscillations during the formation of a drop, the obtainment of the maximum size and the transport of the drop to the liquid metal pool. As can be seen in Figure 5a, the drop is formed at the tip of the wire. However, if distance (height) H (Fig. 4) is excessively long, the drop cannot come into contact with the pool surface. In addition, the instability of filler metal feeding as well as changes in values and directions of metal-vapour jet forces lead to oscillations of the drop (Fig. 5b). The electron beam surfacing of a subsequent layer can result in a situation where metal-vapour jet forces push the drop upwards. The foregoing is triggered by cyclical changes in penetration depth (formation of the gasodynamic channel), and, consequently changes in the volume of the liquid metal pool. Cyclically, where metal-vapour jet forces decrease, the drop moves downwards to the pool. However, it should be noted that the difference between the temperature of the liquid metal pool and that of the metal drop leads to the Leidenfrost effect (*where the liquid drop, when falling on the heated substrate, does not evaporate immediately but temporarily retains its globular shape and moves dynamically*), triggering oscillations of the drop when coming into contact with the liquid metal pool surface.
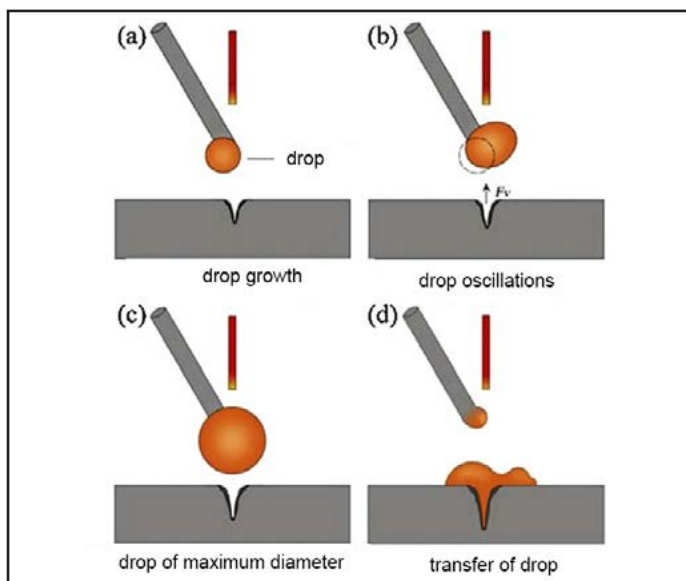
The above-presented mechanism of the liquid metal transfer to the substrate takes place where distance H (height) is excessively long (length of a single drop path). Where height H amounts to 10 mm, the process of liquid metal transport is unstable. A decrease in height H to 6 mm leads to greater diameters of liquid metal drops and to the better quality of overlay welds but, at the same time to irregular face width and excess weld metal height [9].

A further decrease in distance H to the value where the tip of the filler metal wire touches the surface subjected to the process of surfacing is accompanied by a change in the manner of liquid metal transfer in the electron beam. If the filler metal wire feeding rate nearly equals the wire melting rate, the process is stable and a liquid bridge (Fig. 6), responsible for slight pool oscillations, is formed between the tip of the wire and the liquid metal pool [9]. The above-named manner of metal transfer in the electron beam is referred to as the transport over the liquid metal bridge. The above-presented manner of metal transfer is characterised by the fact that the heat necessary for the melting of the filler metal originates in thermal conductivity, radiation from the liquid metal pool and the kinetic energy of electrons. For this reason, the above-named manner of metal transfer accompanying the process of electron beam

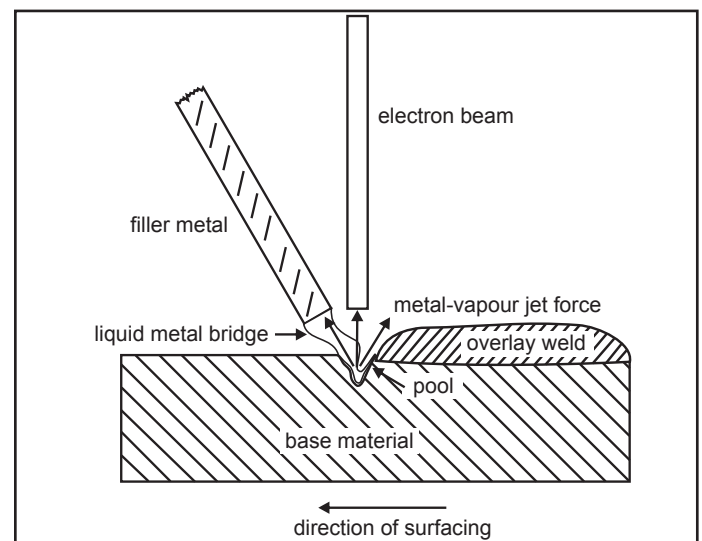Fig. 5. Transport of liquid metal during electron beam surfacing [9]

Fig. 6. Schematic diagram of electron beam surfacing with the liquid metal bridge between the tip of the wire and the liquid metal pool [9]

surfacing is stable within a wide range of technological parameters.

The primary parameters of rapid prototyping involving the use of the electron beam and a wire (deposited material) include accelerating voltage, electron beam current, a travel rate, a vacuum in a working chamber, the diameter of a wire, the grade of a deposited material, the geometrical position of the wire in relation to the electron beam, a wire feeding angle and electrode extension.

Technologically, accelerating voltage is not the most important parameter in the process of rapid prototyping. Accelerating voltage is usually maintained at a constant level of 60 kV. The constant beam current combined with increased accelerating voltage reduces the electron beam diameter, increases the density of energy and is responsible for deeper penetration depth. Overly low accelerating voltage is responsible for the unstable melting of the filler metal. Accelerating voltage along with current affect the electron beam power and the geometry of a single layer. In addition, increased accelerating voltage increases the width and decreases the thickness of a single deposited layer. In turn, increased beam current increases the width of a single layer and penetration depth.

The rate of travel affects the geometry of a single layer and penetration depth. In the process of electron beam-based rapid prototyping the volume of liquid metal is small. An increase in the rate of travel (i.e. relative motion of an object in relation to the beam of electrons or vice versa) is accompanied by a decrease in a heat input per a surfaced layer length unit as well as by a decrease in width and the thickness of a single layer. It should be noted that changes in the travel rate affect the geometry of a deposited layer to a greater extent than accelerating voltage or current.

Vacuum in a working chamber. A vacuum is indispensable for transporting the beam of electrons and its focusing. The presence of gas particles reduces the beam power through the absorption and dissipation of electrons. It is advisable to use a vacuum of $5 \cdot 10^{-3}$ mbar or lower, particularly in relation to titanium alloys. Electron beam rapid prototyping under atmospheric pressure requires the use of specifically designed equipment.

Wire feeding rate. An increase in a wire feeding rate increases the efficiency of rapid prototyping. If a wire feeding rate is excessively high, the tip of the wire may not melt entirely. A welding rate should be the same as a wire melting rate as otherwise the process of deposition is unstable. It should be noted that the wire feeding rate depends on the beam power (accelerating voltage and beam current) and the rate of travel. The use of an advancing wire facilitates the obtainment of a properly deposited layer. If the travel rate is constant, an increase in the filler metal wire feeding rate increases the proportion of the height to the width of a single deposited layer.

Wire feeding method. The manner of deposited material feeding depends primarily on the geometry of the end product. The most popular is the advancing wire. However, in the EBAM technology, particularly in cases of more complicated elements, side feeding is also frequently applied. The use of the advancing wire or side feeding techniques provides the better quality of deposited layers than the use of the dragged wire.

Wire feeding angle. In the process of rapid prototyping the wire feeding angle depends on surface tension (grade of deposited material), the diameter of the electron beam and the distribution of power density in the beam. An angle, at which the wire is fed is usually restricted within the range of 20 to 50°.

The electrode extension (distance between the wire feeding tip and the tip of the wire) affects rapid prototyping stability. The overly short electrode extension is responsible for a greater heat input to the wire feeding tip from the filler metal area, where the rigidity of the wire is maintained and the stability of the

process is higher. The excessively long electrode wire leads to the situation where the tip of the wire is more susceptible to deformations and the dissipation of heat to the wire feeding tip is lower.

Filler metals. It is possible to use both solid and flux-cored wires. Until recently, rapid prototyping involving the use of wires has been applied when making elements in titanium or aluminium alloys, tool steels, corrosion resistant steels and nickel alloys.

One of the most important advantages of electron beam-based additive manufacturing methods is the possibility of performing the process in a vacuum. The entire protection of the deposition area against the access of atmosphere enables the making of elements in reactive materials, e.g. titanium. Subsequent layers of the deposited material are protected against oxidation, and, as a result, the quality and metallurgical purity of the end product is higher than those obtained in gas-shielded processes, e.g. in cases of laser or arc-based technologies. The latter case entails the continuous risk involving the suction of oxygen and/or nitrogen from atmosphere, possibly leading to porosity formation in end products.

Previously performed tests [10] revealed that rapid prototyping technologies involving the use of the electron beam and wires can be used in various missions conducted in outer space. One of such applications could be the construction of large-sized 3D orbital structures having dimensions restricted within tens of metres to one kilometre. Another possibility includes the making of a small-sized multifunctional system, which could be used by astronauts during long search missions to produce spare parts. Another possible application of electron beam-based rapid prototyping in outer space includes the development of a miniaturised system for the monitoring and repair of the structure of the spaceship or the base [10]. Although the deposited material can be applied both as powder and as a wire, the form of a wire should be preferred for using in outer space because of operational and safety-related issues accompanying the application of metallic powder in the environment of microgravity [11].

The concentrated electron beam is characterised by a power efficiency of more than 90%, which makes the former an attractive source of energy usable when making elements applying additive technologies. The vacuum in outer space (up to 10-17 mbar) can be used as the process environment. This eliminates the necessity of building a vacuum chamber and a pumping system typical of a ground-based station. Another issue is X-radiation combined with high accelerating voltage. This risk can be minimised by using lower accelerating voltage and performing deposition processes outside a spaceship (base), where the very spaceship structure provides appropriate protection for astronauts and sensitive equipment [11].

K.M.B. Taminger and R.A Hafley [12] from Nasa Langley Research Center presented results concerning the rapid prototyping involving the use of the electron beam and wire performed under as-on-earth conditions (1G) and in lower gravity. The researchers developed the technology of electron beam freeform fabrication (EBF3). The obtained results were highly promising, particularly in terms of future solutions to be used in space. The authors also demonstrated [13] that the microstructure and mechanical properties obtained in relation to the titanium alloy were comparable with those obtained through forging and that it was possible to obtain high efficiency when making elements having the fine-grained microstructure using additive manufacturing. D. Mitzner et al. [14] demonstrated that electron beam modulation made it possible to refine the microstructure in the titanium alloy. The size of grain β was reduced from 1164 μm to 734 μm. D. Gonzales et al. [15] demonstrated that the use of flux-cored wires containing more aluminium, iron and boron enabled the making of elements of titanium alloy Ti-6Al-4V characterised by

more stable and more refined microstructure.

S. Phinazee [16] performed rapid prototyping tests involving the use of electron beam aimed to make an airframe element of titanium alloy Ti-6Al-4V and stated that the above-named process made it possible to reduce the consumption of material by 79% and the cost of manufacturing from 17 430 to 9 810 USD. M.E. Kinsella [17] demonstrated that the making of an engine frame of nickel alloy 718 using the additive technology lead to savings of 30% in comparison with conventional manufacturing methods.

S. Stecker et al. [18] demonstrated that the total cost related to the manufacturing of single elements falls rapidly along with increasing deposition rates (Fig. 7). The assumptions adopted in calculations were the following: the weight of the end product (element) – 45 kg, the weight of one wire reel – 11 kg, the cost of labour – 250 USD/hour and the cost of wire Ti-6Al-4V – 240 USD/kg. The total cost related to the making of a single element depends on the market price of deposited materials (filler metals) and process efficiency. The cost of filler metals depends on the manufacturing technology, demand and availability of related materials. The efficiency of the rapid prototyping involving the use of alloy Ti-6Al-4V was set at 18 kg/hour. However, it should be noted that the technology is progressive and the obtainment of the efficiency amounting to 23 kg/hour is within reach.
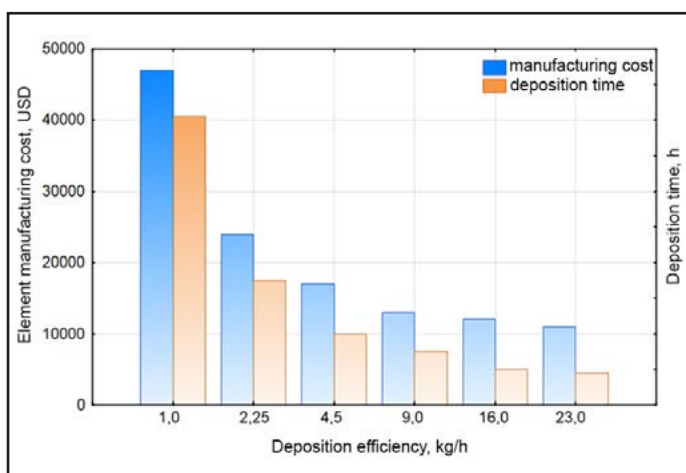

Fig. 7. Effect of rapid prototyping efficiency on manufacturing costs [18]

Summary

In comparison with conventional production technologies such as forging, casting or machining, the manufacturing of elements having a shape similar to an end product, performed layer after layer, using a wire as a deposited material, enables the significant reduction of production-related time and costs. A growing market, particularly in the aviation industry, military or medicine, requires the lot production of elements made of titanium or aluminium alloys, corrosion resistant steels and other materials. Rapid prototyping makes it possible to maintain the complete repeatability of manufacturing elements, the obtainment of material properties not inferior to those obtainable using other technologies and the reduction of material consumption. Rapid prototyping involving the use of the electron beam and the filler metal in the form of a wire is an innovative manufacturing technology enabling the making of complicated three-dimensional elements, particularly of reactive materials (as the process is carried out in vacuum). The further development of the above-named manufacturing method will primarily focus on control systems of additive manufacturing equipment so that elements of more complex shapes could be produced.

Acknowledgements

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