Evaluation of the Technical-Economic Potential of Particle-Reinforced Aluminum Matrix Composites and Electrochemical Machining

A Schubert1,2, U Götze3, M Hackert-Oschätzchen1, N Lehnert1, F Herold3, G Meichsner2, A Schmidt4

1 Technische Universität Chemnitz, Professorship Micromanufacturing Technology, Chemnitz, Germany
2 Fraunhofer Institute for Machine Tools and Forming Technology, Chemnitz, Germany
3 Technische Universität Chemnitz, Professorship of Management Accounting and Control, Chemnitz, Germany

E-mail: franziska.herold@wirtschaft.tu-chemnitz.de

Abstract. Compared to conventional cutting, the processing of materials by electrochemical machining offers some technical advantages like high surface quality, no thermal or mechanical impact on the work piece and preservation of the microstructure of the work piece material. From the economic point of view, the possibility of process parallelization and the absence of any process-related tool wear are mentionable advantages of electrochemical machining. In this study, based on experimental results, it will be evaluated to what extent the electrochemical machining is technically and economically suitable for the finish-machining of particle-reinforced aluminum matrix composites (AMCs). Initial studies showed that electrochemical machining – in contrast to other machining processes – has the potential to fulfil demanding requirements regarding precision and surface quality of products or components especially when applied to AMCs. In addition, the investigations show that processing of AMCs by electrochemical machining requires less energy than the electrochemical machining of stainless steel. Therefore, an evaluation of electrochemically machined AMCs – compared to stainless steel – from a technical and an economic perspective will be presented in this paper. The results show the potential of electro-chemically machined AMCs and contribute to the enhancement of instruments for technical-economic evaluations as well as a comprehensive innovation control.

1. Introduction

The combination of two or more physically and chemically different materials is a composite material. In composite materials, the different materials exist in separated phases. The major phase is the matrix material and the minor phase is the reinforcement. The properties of the composites, such as E-modulus or density, are defined by the matrix material as metal, ceramic or polymer, and by the material and the type, e.g. particle or fiber, of the reinforcement [1].

In the Collaborative Research Centre SFB 692 HALS at Technische Universität Chemnitz inter alia particle-reinforced aluminum matrix composites (AMCs) are investigated. In SFB 692 several academic
institutions analyze and evaluate the potential of AMCs referring to material properties, different methods of machining and economic aspects.

This study is focused on the electrochemical machining (ECM) as a method for finish-machining of AMCs and the evaluation of its technical and economic potential. Electrochemical machining is already industrially established for the machining of tools but also for series production [2]. In this study the technical and economic benefits and drawbacks of a material replacement from stainless steel 1.4301 by an AMC will be evaluated.

2. Evaluation Approach
As this paper deals with issues of two different scientific disciplines, the usage of a methodology contemplating technical as well as economic outcomes and integrating them into a comprehensive evaluation is worthwhile. Amongst others, it is important to have a consistent data base of technical and economic evaluation with regard to process parameters, resource consumption, output quantities and material properties etc. in order to avoid double work and to achieve a high significance of results. The methodology of integrated evaluation applied here [3], offers the option of a structured and integrated technical-economic evaluation of production factors (such as materials), process chains and processes, products (or work pieces) as well as technologies by using three modules: the technical evaluation, the economic evaluation and, finally, the integrated evaluation (figure 1).

The technical evaluation considers technical criteria and applies evaluation methods from engineering sciences. The results of this evaluation are the basis of the subsequent economic as well as integrated evaluation. For the economic evaluation, methods originating from the scientific field of management accounting can be used for calculating economic target figures and analyzing profitability of alternatives. Its results may initiate reconsiderations and further development of technical alternatives in terms of resource efficiency or other targets. Finally, based on technical as well as economic outcomes an integrated evaluation is performed intending to reveal the overall performance of alternatives. In the following, this integrated evaluation approach is applied to the assessment of electrochemically machined AMCs (compared to stainless steel).

3. Technical Evaluation
The electrochemical machining is based on the local anodic dissolution of metallic work pieces. Figure 2 shows a scheme of the dissolution during electrochemical machining.

The work piece is the anode and the tool is the cathode. Between these two electrodes is the working gap, flushed by electrolyte. By applying an electric potential to the electrodes complex electrochemical reactions occur in the electrolyte. As a result, the work piece dissolves by emitting ions into the electrolyte [2, 4, 5].
During the electrochemical machining process temperatures are below 80 °C. Furthermore, no mechanical contact of work piece and tool exists, so no process-related tool wear occurs. Because of the low temperature and the lack of contact, the micro-structure of the work piece is barely influenced [2, 4, 5].

The investigations on finish-machining of AMCs by ECM were performed inter alia by the pulsed electrochemical machining (PECM) with oscillating cathode. The experimental analysis in this study was performed with a PEMCenter 8000 from PEMTec SNC, France. The PEMCenter 8000 is a system containing an electrolyte preparation system, a power supply, a control unit and the process chamber.

For the process design and the economic evaluation, the electrochemical dissolution characteristic of the work piece material is needed. This characteristic is hard to predict and should be determined experimentally. For this experimental characterization, an experimental setup was developed which is shown in figure 3.

The cathode is fed vertically down towards the AMC specimen. Both have cylindrical shapes with a diameter of 12 mm. The electrolyte is supplied in horizontal direction through the working gap which
leads to a good electrolyte replacement. With this experimental setup, the electrochemical dissolution characteristic of stainless steel 1.4301 and the AMC consisting of EN AW 2017 + 10 % SiC-particles were determined [6, 7].

One possibility for describing the electrochemical dissolution characteristic is the current efficiency $\eta$, which is calculated by using equation (1).

$$\eta(J) = \frac{V_{\text{eff}}(J)}{V_{\text{sp}}}$$  \hspace{1cm} (1)

The current efficiency is the quotient of the effectively removed volume $V_{\text{eff}}(J)$ and the theoretically removable volume $V_{\text{sp}}$ based on Faraday’s law. Since the effectively removed volume depends on the current density $J$, the current efficiency depends on current density as well. Figure 4 shows the current efficiency as a function of the current density of stainless steel 1.4301 and the analyzed AMC which are machined by using NaNO$_3$ electrolyte.

It can be seen that the functions for the two materials differ significantly. The current efficiency of the AMC is above 90 % in the investigated range of the current density. The maximal value is 110 %. This is characteristic for an active dissolution. In contrast, the current efficiency of the stainless steel is 0 % for small current densities and rises rapidly between 10 A/cm$^2$ and 30 A/cm$^2$ up to a maximal value of 70 %. The stainless steel shows a trans passive dissolution characteristic. Due to the active dissolution the removal rate of the AMC is higher than that of the stainless steel. By the experimental results it can be derived additionally, that for a current density of 50 A/cm$^2$ the removable volume per coulomb of the AMC has a value of approximately 0.042 mm$^3$/C while the value of the stainless steel is approximately 0.019 mm$^3$/C.

As a result, ECM shows a considerable potential for finish-machining of AMCs. Thereby, the current efficiency of the investigated AMC is significantly higher than the current efficiency of the stainless steel. This means that a defined volume of AMC can be removed electrochemically in distinctly less time than the same volume of 1.4301.

For the economic evaluation, a work piece with an initial volume of 3800 mm$^3$ and an end volume of 2600 mm$^3$ is taken as basis. This work piece is formerly made of stainless steel 1.4301 and should be made of AMC in future. Based on technical evaluation, the work piece made of AMC can be machined
faster. Besides, the density of the AMC (2.9 g/cm$^3$) is about a third of the density of stainless steel 1.4301 (7.9 g/cm$^3$). When switching from steel to AMC, however, the lower E-modulus must be regarded (200 GPa for 1.4301 and 115 GPa for the AMC). Additionally, the economic evaluation has to consider that the process chain consists of the electrochemical machining process in a strict sense and the cleaning of the work pieces afterwards in the case of AMCs as well as steel.

4. Economic Evaluation

For a structured economic and integrated evaluation of innovative (and often complex) products, processes, production factors (such as materials) and combinations of these object types, a procedure model has proven to be worthwhile [8–11]. This model is characterized by a hierarchical breakdown of the evaluation task as well as a decision theory-based sequence of six steps at each level:

1. Determination of evaluation goal(s), requirements on the evaluation task, evaluation scope, and system boundaries
2. Determination of relevant target figure(s)
3. Identification, preselection, modelling and analysis of alternatives
4. Identification, analysis and forecast of relevant influencing factors (scenarios)
5. Determination of target figure(s) outcomes
6. Comparison, sensitivity analysis, interpretation

In the following, the procedure model will be applied to the economic evaluation of electrochemical machining of AMCs and the resulting AMCs. Correspondingly, the evaluation goal is the economic assessment of the process chain of electrochemical machining as well as the machined AMCs compared to stainless steel. The requirements on the evaluation task comprise a preferably high transparency as well as significance. The evaluation scope includes the process chains of AMCs and stainless steel with the relevant processes of electrochemical machining (in a strict sense) and final cleaning as well as the properties of the work piece (part). The evaluation is based on a laboratory scale for particle reinforced aluminum matrix composites (AMCs) and on the data ascertained in the SFB 692. In industrial applications, cost-saving effects like volume discounts for materials may appear that cannot be included here. The related system boundaries are the start and the end of the manufacturing process; at these points, amongst others, the properties of the raw material and of the output (work piece with machined and cleaned AMCs/steel) have to be determined.

Within the second step of the procedure model, one or more target figures have to be determined. Here, it is assumed that the properties of the output of electrochemically machined AMCs/steel enable the applicability of both in a couple of fields and effects of these properties on revenues can be neglected. Furthermore, for means of simplification, the monetary effects of possibly different output quantities will not be considered. Additionally, a dynamic calculation does not seem to be necessary. Then, costs are an appropriate economic target figure for the evaluation of the process chain as well as its output [12]. Corresponding with the target figure, the evaluation methods should be chosen. For forecasting costs of innovative processes, methods of cost accounting (such as calculation with activity units [12] and the related activity based costing [13, 14]) and/or development-concurrent cost-calculations [15, 16] can be used, in general. In the following, a specific variant of calculation with activity units is applied.

In the third step, the alternatives have to be identified, preselected, modelled and analyzed. Here, the alternatives are AMCs and stainless steel 1.4301 each manufactured by electrochemical machining. The results of the technological analysis of the output materials have already been presented in section 3. Each of the manufacturing process chains consists of the processes of electrochemical machining in the strict sense (described for AMCs in section 3 as well) and final cleaning. Main production factors used in these process chains are material (AMCs and stainless steel), energy, machinery and equipment (PEMCenter 8000)), labor (one employee who has to insert and remove the parts into and from the machine and another employee for cleaning), and production space. The economic evaluation has to refer to the consumption of these factors – correspondingly, material costs, energy costs, (other) machine-dependent costs such as depreciation, maintenance costs, imputed interest, labor costs and
occupancy costs have to be taken into account. The evaluation also has to consider the main differences between the process chains and the materials: The processing time of steel (for electrochemical machining in a strict sense) is longer due to a smaller removable volume per coulomb resulting in higher energy consumption. This longer processing time results in higher machine-dependent costs and possibly labor costs; in contrast, material costs of AMCs are considerably higher and more maintenance activities are expected to be necessary for them since the filter used in the process of electrochemical machining requires more cleaning/replacement due to the existence of particles.

At the fourth step, relevant (cost) influencing factors are identified, analyzed and forecast. These comprise factors from inside a company: Output volume, processing time and transition time, labor time, needed space as well as other input-, process- and output-related factors such as current density and removable volume. Additionally, external factors are relevant, especially factor prices such as energy prices, hourly wage rates, interest rates, asset costs. Material costs are strongly depending on the output volume. For energy and other machine-dependent costs, the processing time is the decisive influencing factor, labor costs are strongly related with the labor time (and thus, processing as well as transition time), occupancy costs depend on the needed space. Thus, following the logic of calculation with activity units for these cost categories processing time, labor time and space are used as activity units and the corresponding costs are calculated based on them.

In case of different possible outcomes of these factors, several scenarios (as specific constellations of various outcomes of the influencing factors) can be modelled and analyzed. Here, a first differentiation of scenarios is made referring to different output volumes and the corresponding outcomes of other influencing factors, e.g. processing time. For a laboratory scale, the simultaneous processing of 4 parts (= one batch) with the machine PEMCenter 8000 is assumed. This output volume is considered as a starting point for calculation. A higher output volume of 100,000 parts is chosen for means of comparison.

Based on the results of the previous steps, target figure outcomes will be determined in the fifth step. As mentioned above, a specific variant of cost calculation with activity units is conducted for electrochemical machining of AMC as well as stainless steel. Therefore, firstly the total amount of the relevant cost categories has to be determined based on the expected outcomes of the influencing factors and corresponding activity units, then costs per activity unit are calculated and finally the process costs are derived based on the number of activity units needed by the process.

At first, the machining of AMC work pieces is examined. For calculation of the machine-dependent costs, several further assumptions regarding the machine have to be made. Amongst others, a maximum machine operation time (of 365 days and 24 hours per day minus maintenance time) is expected; maintenance time amounts to 48 hours per year. The initial investment outlay for the machine is 500,000 € and the economic life of the machine is assumed to be 25 years with a liquidation value of 0. Current density and amount to 2,100 € per year. The imputed interest is calculated by multiplying the annual price of 82.88 €/kWh as well as a power consumption of 1.4 kWh per work piece are estimated (the latter based on technical calculations). Occupancy costs are determined on the basis of average rent values and heating costs for factories in Chemnitz. Hence, an annual price of 82.88 € per square meter has been taken into account. For determining labor costs, again different scenarios may be realistic. One is that the employee works only in this process chain and cannot
do other work (scenario 1). In that case, the relevant labor times are the processing times of electrochemical machining as well as the cleaning process. In the second extreme case (scenario 2) the employee would be capable of doing other work during the total processing of electrochemically machining (including transition). Then, the relevant times are the transition time and the processing time of the cleaning process (the electrochemical machining is an automated process). Of course, scenarios between these extreme cases may also be realistic. In each case, the labor costs are calculated by multiplying the resulting times (in hours) by the assumed hourly wage rate of 50 € (including incidental wage costs). Tab. 1 shows the results of the cost calculation for the process chain of electrochemical machining of AMCs for both scenarios.

The results show that – due to the underlying assumptions – all cost elements show a linear dependency on the output volume. Correspondingly, the costs per unit are constant. In scenario 1, labor costs are almost six times higher because of the inability of using the workforce during the processing time of electrochemical machining. Correspondingly, the total costs are considerably higher.

**Table 1.** Total costs and costs per part for electrochemical machining of AMCs for scenario 1 and scenario 2.

| Process chain            | Scenario 1 | Scenario 2 |
|--------------------------|------------|------------|
|                          | 4 parts    | 100,000 parts | 4 parts    | 100,000 parts |
| Electrochemical Machining|            |            |            |            |
| Processing time          | 3.00 min   | 75,000.00 min | 3.00 min   | 75,000.00 min |
| Transition time          | 0.50 min   | 12,500.00 min | 0.50 min   | 12,500.00 min |
| Depreciation             | 0.11 €     | 2,869.61 €   | 0.11 €     | 2,869.61 €   |
| Maintenance costs        | 0.01 €     | 301.31 €     | 0.01 €     | 301.31 €     |
| Imputed interest         | 0.06 €     | 1,434.80 €   | 0.06 €     | 1,434.80 €   |
| Labor costs              | 2.50 €     | 62,500.00 €  | 0.42 €     | 10,416.67 €  |
| Energy costs             | 0.04 €     | 980.00 €     | 0.04 €     | 980.00 €     |
| Occupancy costs          | 0.01 €     | 321.09 €     | 0.01 €     | 321.09 €     |
| **Total process costs**  | **2.74 €** | **68,406.81 €** | **0.65 €** | **16,323.47 €** |
| Cleaning                 |            |            |            |            |
| Processing time          | 20.00 min  | 500,000.00 min | 20.00 min  | 500,000.00 min |
| Labor costs              | 16.67 €    | 416,666.67 €  | 16.67 €    | 416,666.67 €  |
| **Total process costs**  | **16.67 €** | **416,666.67 €** | **16.67 €** | **416,666.67 €** |
| Manufacturing costs      |            |            |            |            |
|                          | 19.40 €    | 485,073.47 €  | 17.32 €    | 432,990.14 €  |
| Material costs           | 4 parts    | 100,000 parts | 4 parts    | 100,000 parts |
| Basic raw material (AMC) | 3.771 €    | 94,270.00 €   | 3.771 €    | 94,270.00 €   |
| Electrolyte (NaNO3)      | 0.001 €    | 35.87 €       | 0.001 €    | 35.87 €       |
| Material costs           | 3.772 €    | 94,305.87 €   | 3.772 €    | 94,305.87 €   |
| **Total costs**          | **23.18 €** | **579,379.34 €** | **21.09 €** | **527,296.01 €** |
| Costs per part           | 5.79 €     | 5.79 €        | 5.27 €     | 5.27 €

In the next step, the process chain costs for AMCs are compared to the costs for processing stainless steel 1.4301. Due to the longer processing time, most of the processing time-dependant cost items of the steel variant are higher than those of AMCs: depreciation, imputed interest, maintenance costs, occupancy costs and energy costs. In contrast, the material costs for the basic raw material are lower when producing stainless steel work pieces. Finally, the labor costs of processing AMC as well as steel
are equal for scenario 2, because the transition time of electrochemical machining and the processing time of the cleaning process are identical. The resulting total costs and costs per part of processing stainless steel 1.4301 by ECM are shown in table 2 for both scenarios. Again, under the assumption of scenario 1 the labor costs and corresponding manufacturing costs of processing stainless steel will be considerably higher than that of scenario 2.

Table 2. Total costs and costs per part for electrochemical machining of stainless steel for scenario 1 and scenario 2.

| Process chain             | Scenario 1          | Scenario 2          |
|---------------------------|---------------------|---------------------|
|                           | 4 parts | 100,000 parts | 4 parts | 100,000 parts |
| Electrochemical Machining |         |               |         |               |
| Processing time           | 15.00 min | 375,000.00 min | 15.00 min | 375,000.00 min |
| Transition time           | 0.50 min | 12,500.00 min | 0.50 min | 12,500.00 min |
| Depreciation              | 0.57 €   | 14,348.03 €   | 0.57 €   | 14,348.03 €   |
| Maintenance costs         | 0.05 €   | 1,291.32 €    | 0.05 €   | 1,291.32 €    |
| Imputed interest          | 0.29 €   | 7,174.01 €    | 0.29 €   | 7,174.01 €    |
| Labor costs               | 12.50 €  | 312,500.00 €  | 0.42 €   | 10,416.67 €   |
| Energy costs              | 0.20 €   | 4,900.00 €    | 0.20 €   | 4,900.00 €    |
| Occupancy costs           | 0.06 €   | 1,605.45 €    | 0.06 €   | 1,605.45 €    |
| Total process costs       | 13.67 €  | 341,818.81 €  | 1.59 €   | 39,735.48 €   |

| Cleaning                  |         |               |         |               |
| Processing time           | 20.00 min | 500,000.00 min | 20.00 min | 500,000.00 min |
| Labor costs               | 16.67 €  | 416,666.67 €  | 16.67 €  | 416,666.67 €  |
| Total process costs       | 16.67 €  | 416,666.67 €  | 16.67 €  | 416,666.67 €  |

| Manufacturing costs       |         |               |         |               |
|                           | 30.34 €  | 758,485.48 €  | 18.26 €  | 456,402.14 €  |

| Material costs            | 4 parts | 100,000 parts | 4 parts | 100,000 parts |
|---------------------------|---------|---------------|---------|---------------|
| Basic raw material (stainless steel) | 1.458 €  | 36,450.00 €  | 1.458 €  | 36,450.00 €  |
| Electrolyte (NaNO3)       | 0.007 €  | 179.35 €     | 0.007 €  | 179.35 €     |
| Material costs            | 1.465 €  | 36,629.35 €  | 1.465 €  | 36,629.35 €  |
| Total costs               | 31.80 €  | 795,114.83 € | 19.72 €  | 493,031.49 € |
| Costs per part            | 7.95 €   | 7.95 €       | 4.93 €   | 4.93 €       |

The last step of the procedure model consists of the comparison, sensitivity analysis and interpretation of the outcomes. As tables 1 and 2 show, for scenario 2 the total costs (and costs per part) of processing stainless steel are slightly lower than that of AMC for every production volume considered. Under scenario 1, the result is different. Here, the total costs of electrochemically machined AMCs are lower than that of steel for all production volumes due to the stronger influence of the longer processing time of steel (resulting in five times higher labor costs). This shows that the economical advantageousness of materials and their processing will depend on the characteristics of the production system.

Concluding, it has to be admitted that a couple of simplifying assumptions have been made concerning the calculations. One of them is the supposition of linear relationship between machine operation time (transition and processing time) and costs. Thus, learning effects and other economies of scale effects such as declining factor prices are neglected. Some of these assumptions may be cancelled or modified in the integrated technical-economic evaluation, the last element of the evaluation approach.
5. Integrated Technical-Economic Evaluation
An integrated technical-economic evaluation is necessary if not all of the decision-relevant technical features and/or their influences have been included in the economic evaluation. It can be conducted in different ways: by building a list of additional arguments for or (dis)advantages of the alternatives, by visualizing measures for the technical and economic attractiveness or profitability in diagrams [19] or by using multi-criteria decision-making methods such as utility value method [17]. Here, for sake of simplification and due to the restricted extent of the paper, the first option is chosen.

A first additional point concerns the lower processing time of AMCs compared to steel. This difference does not only influence costs (as considered in section 4) but also the maximum output quantity of the process chains which is considerably larger for AMCs. Thus, also the achievable revenues and the corresponding margins tend to be higher. Secondly, AMCs are currently at an earlier stage of the life cycle compared to stainless steel. Thus, more improvements and cost reductions have to be expected.

Furthermore, the properties of the materials and their influence on the work pieces have to be considered. The most important differing properties are the density and the E-Modulus (see section 3). As shown, the density of AMC is more than two times lower than that of stainless steel 1.4301. In terms of weight saving, this implies that parts consisting of AMC are more than two times lighter than comparable stainless steel parts. This property is inquired especially for lightweight construction in the automobile or aircraft industry. In these industries, already slight weight reductions result in notable economic benefits that justify higher prices of the material/parts. The economic evaluation indicates that the costs of AMC parts are not extensively higher than that of stainless steel parts (if they are higher at all). For being advantageous, the economic benefit of using AMCs should exceed the additional costs. For example, in aircraft industry, a weight saving of one kilogram results in a monetary benefit between 100 and 500 € [18]. Thus, it can be assumed that this technical property of AMCs generates a considerable economic potential. Indeed, it has also to be taken into account that the E-Modulus of AMC is only half as large as that of stainless steel. This implies a lower ductility. Thus, AMC parts should be used when lightweight is more important than ductility and not for highly stressed parts.

6. Summary and Outlook
In this paper, the procedure of electrochemical machining of AMCs as well as the resulting AMCs have been evaluated from a technical as well as economic point of view. After presenting an integrated evaluation approach, the processing of electrochemical machining has been described and a technical evaluation of electrochemical machining of AMC compared to stainless steel has been conducted. Based on this, the process chains of electrochemical machining of AMCs and steel were evaluated by cost calculation. The results show relatively small differences of total costs with the results strongly depending on the scenarios. The integrated evaluation finally reveals additional advantages of AMCs in terms of smaller capacity utilization and above all a lower density generating a high potential for lightweight applications. Further work should be directed to refining the methodology with respect to the modelling of production scenarios and cost functions as well as its verification by applying the methods in industrial practice. Furthermore, the studies should be extended to life cycle assessment in order to include ecological effects and thereby the contribution of the entire process chains and materials to sustainability.

Acknowledgment
We gratefully thank the Deutsche Forschungsgemeinschaft (DFG) for funding this work within the Collaborative Research Centre SFB 692.

References
[1] Chawla K K 2012 Composite Materials 3rd ed. (New York: Springer)
[2] Hackert-Oschätzchen M 2015 Gestaltung von elektrochemischen Abtragprozessen durch Multiphysiksimulation gezeigt an der Endformgebung von Mikrobohrungen
Habilitationsschrift (Verlag Wissenschaftliche Scripten)

[3] Götze U, Koriath H J, Kolesnikov A, Lindner R and Paetzold J 2012 Integrated methodology for the evaluation of the energy- and cost-effectiveness of machine tools CIRP J. Manuf. Sci. Technol. 5 3 151–163

[4] Klocke F and König W 2007 Fertigungsverfahren 3. Abtragen, Generieren und Lasermaterialbearbeitung 4th ed. (Berlin Heidelberg: Springer)

[5] Schubert A, Meichsner G, Hackert-Oschätzchen M, Zinecker M and Edelmann J 2011 Pulsed Electrochemical Machining of Powder Metallurgy Steels Proc. 7th Int. Symp. Electrochem. Mach. Technol 68–75

[6] Schubert A, Hackert-Oschätzchen M, Lehnert N, Martin A and Meichsner G 2015 Analysis of the Electrochemical Dissolution Characteristics of High-Strength Particle Reinforced Aluminum Matrix Composites ICSMA-17

[7] Schubert A, Meichsner G, Boenig L, Hackert-Oschätzchen M, Krönert M and Edelmann J 2013 Resource-Efficient Design of Precise Electrochemical Machining Proc. 9th INSECT 53–64

[8] VDI-Richtlinie 2221 1993 Methodik zum Entwerfen und Konstruieren technischer Systeme und Produkte 5th ed. (Düsseldorf: VDI)

[9] Götze U, Hertel A, Schmidt A, Päßler E and Kaufmann J 2014 Integrated Framework for Life Cycle Oriented Evaluation of Product and Process Technologies: Conceptual Design and Case Study Technology and Manufacturing Process Selection ed E Henriques et al (London: Springer) 193–215

[10] Götze U, Schmidt A and Weber T 2010 Vorgehensmodell zur Abbildung und Analyse des Lebenszyklusprozesses von Werkstoffen – Konzeption und beispielhafte Veranschaulichung Materialwiss. Werkstofftech. 41 6 464–475

[11] Laux H, Gillenkirch R M and Schenk-Mathes H Y 2014 Entscheidungstheorie 9th ed. (Berlin Heidelberg: Springer)

[12] Götze U, Hache B, Schmidt A and Weber T 2011 Methodik zur kostenorientierten Bewertung von Prozessketten der Werkstoffverarbeitung Materialwiss. Werkstofftech. 42 7 647–657

[13] Kaplan R S and Anderson S R 2007 Time-driven activity-based costing: A simpler and more powerful path to higher profits (Boston, Mass.: Havard Business School Publishing)

[14] Bhimani A, Horngren C T, Datar S M and Rajan M V 2012 Management and Cost Accounting 5th ed. (Harlow et al: Financial Times/Prentice Hall)

[15] Ehrlegik K, Kiewert A und Lindemann U 2007 Cost-Efficient Design ed M S Hundal (Berlin Heidelberg: Springer)

[16] Konarsky M, Götze U and Leidich E 2014 An IT-based cost information system for cost planning and monitoring in customized single-unit production. Re-Engineering Total Cost Management. Proc. of ICEC 2014 - IX World Congress 20.-22.10.2014

[17] Götze U, Northcott D and Schuster P 2015 Investment Appraisal Methods and Models 2nd ed. (Berlin Heidelberg: Springer)

[18] Reuter M 2014 Methodik der Werkstoffauswahl. Der systematische Weg zum richtigen Material 2nd ed. (München: Hanser)

[19] Peças P, Ribeiro I and Henriques E 2014 Life Cycle Engineering for Materials and Technology Selection: Two Models, One Approach Procedia CIRP 15 543–548