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Particle-Reinforced Aluminum Matrix Composites (AMCs)—Selected Results of an Integrated Technology, User, and Market Analysis and Forecast

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Abstract: The research and development of new materials such as particle-reinforced aluminum matrix composites (AMCs) will only result in a successful innovation if these materials show significant advantages not only from a technological, but also from an economic point of view. Against this background, in the Collaborative Research Center SFB 692, the concept of an integrated technology, user, and market analysis and forecast has been developed as a means for assessing the technological and commercial potential of new materials in early life cycle stages. After briefly describing this concept, it is applied to AMCs and the potential field of manufacturing aircraft components. Results show not only technological advances, but also considerable economic potential—the latter one primarily resulting from the possible weight reduction being enabled by the increased yield strength of the new material.

Keywords: aluminum matrix composites; light-weight materials; aircraft industry; integrated technology; user; and market analysis and forecast; cost and revenues

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1. Introduction

By the reinforcement of aluminum materials, improved mechanical properties can be achieved [1,2], which is promising for applications, e.g., in automotive or aircraft industries. However, corresponding research and development activities are in an early stage, the transferability of their results in industrial applications is uncertain, and high risks exist. Usually it takes a long time to introduce new materials into the automotive and the aircraft industry. Against this background, it is important to appraise the technological, as well as commercial, potential [3] of the material innovation as early as possible. For appraisal, the methodology of an integrated technology, user, and market analysis and forecast is suggested.

Firstly, this paper presents the basic structure of the methodology which has been explored and elaborated in the Collaborative Research Center SFB 692 [4,5]. Secondly, selected results of the technology analysis and forecast, as well as user and market analysis and forecast of powder-metallurgically produced particle-reinforced aluminum matrix composites (AMCs) [6–10] are outlined and reflected. Finally, conclusions are drawn. The results will give some evidence about the technological, as well as commercial, potential of AMCs, can be used for directing research activities, and—in case a sufficient technology maturity can be achieved—might contribute to their dissemination on the markets.

2. Methodology

For the appraisal of the commercial potential of a new technology, profound knowledge about the potentials and disadvantages of this technology, the requirements and other characteristics of potential users, and the market seems to be necessary. In order to contribute to the enhancement of instruments of a systematic and effective innovation control, in the SFB 692 such a methodology of an integrated technology, user, and market analysis and forecast has been explored and elaborated [4,5]. Technology analysis and forecast comprises the description and classification of the technology as well as the view on competing technologies. In this paper, properties of powder-metallurgically produced AMCs are described and compared to a reference matrix material without any reinforcements and a commercially-available AMC (Duralcan) produced by means of a melt-metallurgical production method. User analysis and forecast deals with the identification of potential application fields and potential users in different stages of the value chain, the requirements and demands of these users, as well as their willingness to pay. Therefore, it has to comprise an analysis of innovation-dependent costs and benefits which are relevant from the perspective of users. For this task, life cycle costing as well as (other) instruments for the cost (and revenue) appraisal of material, product, and process technologies are available [11]. Since a commercialization can only succeed if the new technology fits the requirements and demands, this has to be checked particularly. Market analysis and forecast is intended to characterize the market and competitors and to forecast their performance. Finally, technology appraisal integrates the results of analyses and forecasts to an overall appraisal of the economic potential of a new technology. Figure 1 shows the basic structure of the methodology.

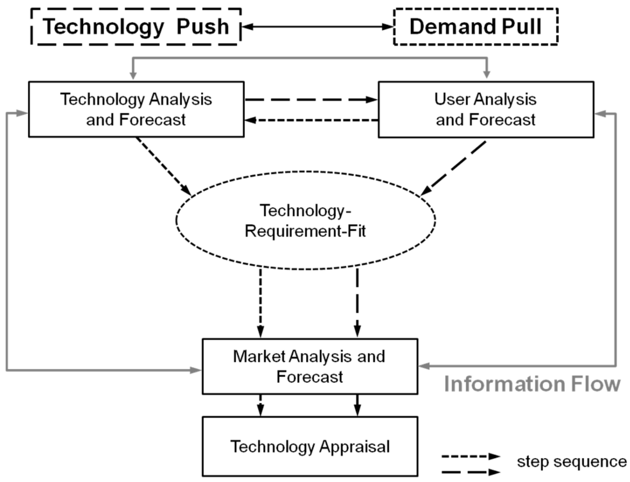


Figure 1. Basic structure of an integrated technology, user, and market analysis and forecast [4].

The arrangement of the several analysis and forecast components depends on the fact if innovations are pushed onto the market (technology push) or if they are developed because of concrete demand of users (demand pull). In case of a technology push (as it is intended in the case of powder-metallurgically produced particle-reinforced aluminum matrix composites) it has to be questioned initially what the new (material and process) technology can accomplish, which benefit can be derived, and who can benefit. Then it has to be clarified which users (characterized by specific requirements, demands, and willingness to pay) could apply the new technology in which stage of the value chain. If the technology fits the requirements, a market analysis can be realized within a third step, followed by an appraisal of the commercial potential of the technology. Sections 3–5 show selected results and more methodical details of the integrated technology, user, and market analysis and forecast applied to powder-metallurgically produced AMCs.

3. Aluminum Matrix Composites Produced by Means of Mechanical Alloying—Technology Analysis and Forecast

Aluminum materials are reinforced in order to improve the mechanical properties, such as the Young's modulus, the tensile strength, the yield strength, and the wear resistance [1,12]. The intensity of the individual improvement on the properties due to the reinforcement depends heavily on the type, size, amount, and distribution of the reinforcement particles. To achieve the desired properties, a high degree of dispersion, complete embedding of the particles within the metal matrix, and the development of a suitable interface are required [2,13]. In general, the smaller the particles, the higher the possible property improvement, but the more difficult the manufacturing becomes.

The production of particle-reinforced aluminum matrix composites (AMC) can be realized by two different ways, the powder-metallurgical and the melt-metallurgical processing. The first presents significant advantages regarding material properties. The latter is not suited to reach a high dispersion degree of nano-scaled particles in a metal matrix. Furthermore, the small particles would react with the melt and disappear or form undesirable phases [14,15]. Therefore, powder-metallurgical techniques are focused in the SFB 692 and in this paper. For this purpose, the methods high-energy ball milling, hot isostatic pressing, and warm extrusion are used. First step is the manufacturing of the composite powders (metallic powder dispersed with particles) by means of high-energy ball milling (HEBM). It provides a homogeneous distribution of the reinforcement particles. The formation of the final composite powder goes through several stages, which is typical for ductile-brittle powder systems (Figure 2). Due to the high ductility of the Al-powder, the first stage of the milling process is characterized by the formation of deformed flat Al-particles with a simultaneous attachment of the SiC-reinforcement to the surface of these flakes. In the next stage, the cold welding of the flakes amongst themselves dominates and leads to the production of large composite particles with lamellar structure (mixture of alternating reinforced and unreinforced lamellae). Further milling of the lamellae causes an increase in mixing and, thus, an improvement of the degree of dispersion.

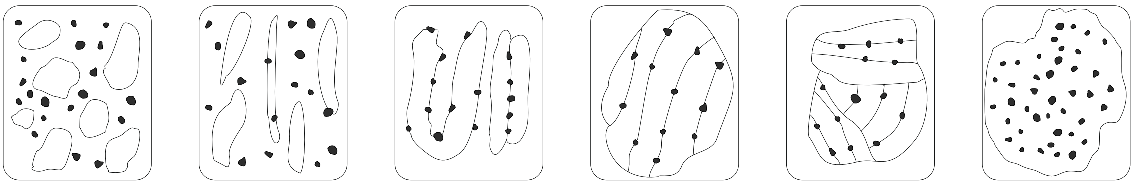


Figure 2. Schematic formation of composite powder during high energy ball milling (based on [16]).

The composite powders have to be compacted in a subsequent step. A compaction method which leads to fully dense materials is the hot-isostatic pressing. It is able to transfer the composite powders into semi-finished products. Due to high scalability, the production on an industrial scale is easily possible.

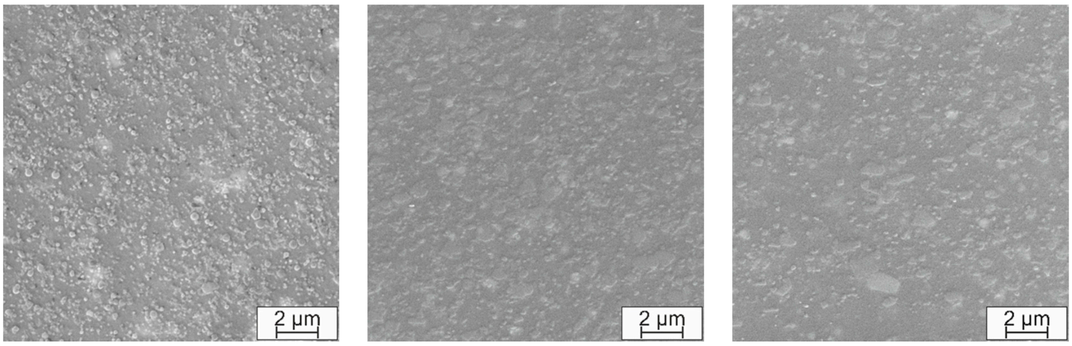
The data used within this article has been determined as part of the Collaborative Research Center SFB 692. The production of the materials and their analysis was carried out under the conditions outlined below.

The aluminum alloy that was used as matrix material was supplied in the form of a commercial, gas-atomized, spherical powder with a particle size fraction <100 µm. The chemical composition (in weight-percent) of the alloy was about 4.1% Cu, 0.7% Mg, 0.8% Mn, 0.1% Si, 0.2% Fe, balance Al. Fine-grained SiC alpha phase powder with a fraction of about 1 µm, as well as a nano-sized beta phase with a fraction size smaller than 200 nm were used as reinforcing components. The preparation of the AMCs was carried out for the three volume fractions 5, 10, and 15 percent by volume.

The composite powder was processed in a high-energy ball mill Simoloyer® CM08 from Zoz Company (Wenden, Germany). Milling was performed for at least four hours in air atmosphere. Details on the preparation of this kind of AMCs are already published in [6–10].

Compaction for all materials was then performed by hot isostatic pressing at 450 °C for 3 h and at a pressure of 1100 bar. Finally, the material was extruded in a temperature range between 355 and 370 °C to produce semi-finished square bars with a cross-section of 15 × 15 mm. The extrusion was performed with a punch speed of 2 mm/s and an extrusion ratio of 42:1.

For the characterization of strength and ductility, cylindrical tensile specimens (with an aspect ratio of the gauge length of three) were machined from the billets in the direction of extrusion. Quasi-static tensile tests were performed at room temperature in a conventional testing machine (Zwick-Roell) with a constant cross-head speed corresponding to an initial strain rate of 10^{-3} s^{-1}. At least three tests were performed for the different material conditions, in particular to provide better statistics on fracture strains of the AMCs. Figure 3 shows three AMCs produced in this way. Some related material characteristics are listed in Table 1.



(**a**) (**b**) (**c**)

Figure 3. SEM images of AMCs produced by means of high-energy ball milling, hot isostatic pressing and extrusion in the T4 condition; matrix alloy AA2017; reinforced with SiC particles: (**a**) 15 vol % β-phase with size < 0.2 µm; (**b**) 15 vol % α-phase with size < 1 µm; and (**c**) 10 vol % α-phase with size < 1 µm.

Table 1. Selected properties of powder-metallurgically produced AMCs compared to the reference matrix material without any reinforcements and a commercially available AMC (Duralcan) produced by means of a melt-metallurgical production method.

	Reference Material			EN AW-2017 AMC Materials		
	AA 2017	Duralcan	Duralcan	(PVW Production)		
	T4 *1	F3S20S *2 Cast	F3S20S *2 Extruded	T4 (a)	T4 (b)	T4 (c)
SiC content in vol %	none	20	20	15	15	10
SiC size in µm	-	12	12	0.2	1.0	1.0
Tensile strength in MPa	425	218	355	683	630	580
Yield strength in MPa	275	191	253	540	480	465
Elongation in %	22.0	0.4	2,8	5.5	5.0	12.0
E modulus in GPa	73	99	113	92	100	90
α *3 in 10^{-6} K^{-1}	23.4	17.1	17.1	18.9	17.9	19.5
K *4 in W/m K	141	192	192	123	126	133

*1 [17]; *2 [18]; *3 Thermal expansion coefficient; *4 Thermal conduction.

The authors have also already dealt with the fatigue behavior of AMCs [19,20]. On the one hand, it becomes clear that an improvement is achieved especially at high load amplitudes above 150 MPa. On the other hand, the behavior at stress amplitudes below 140 MPa is critical, since a fatigue limit does not occur. The causes are often larger intermetallic precipitations resulting from contaminations. A particularly high quality of the composites is, therefore, a basic requirement for applications with cyclic loading. Further specific investigations of the material behavior are indispensable for the transfer into the concrete application.

4. User and Market Analysis and Forecast

As a base for the appraisal of the commercial potential of the properties of powder-metallurgically produced AMCs, *user analysis and forecast* has to identify application fields and potential users and has to analyze users' requirements and willingness to pay for the improved properties. For this, market research instruments, expert interviews, database analyses, creative techniques, instruments of requirements management, such as quality function deployment, the lead user-approach, as well as life cycle costing and (other) instruments for the cost (and revenue) appraisal can be used [5]. Potential application fields of AMCs can be derived from those of materials with similar properties captured by material data bases. For example, the aluminum material data sheets edited by the German Institute for Standardization (DIN) highlight a high mechanical strength, a high fatigue strength, as well as (very) good machining characteristics as essential characteristics of the material EN AW 2017A. Derivable typical applications are high-strength structural components in aircraft construction, automotive engineering, or machine construction [5,21]. Since aircraft construction seems to be a quite promising field of application at a first glance, it is focused in the following considerations.

In addition to titanium, steel, and composite materials, aluminum is a major aircraft material. In aircraft construction, aluminum alloys are especially used in structural components of the fuselage and the airfoil wings [22,23]. From the perspective of an aircraft component manufacturer as potential user, relevant requirements and demands of airlines (regarding properties of aircrafts) and aircraft manufacturers (regarding properties of aircraft components) are important to be analyzed and forecast. A high strength, damage tolerance, as well as corrosion and fatigue resistance, a low weight, good machinability, and low costs are requirements to be considered for the materials [5,22,23]. Concrete, specified requirements can be identified, analyzed, and forecast by the cooperation with a potential lead user (e.g., an aircraft component manufacturer). Lead users are users whose needs become general in the future. They are familiar with current and potential future conditions, can provide design data and experience for specifying requirements [24]. Although specified data are not available in this case until now, it can be assumed that the improved (tensile and yield strength, thermal conduction) or at least competitive (E modulus, thermal expansion) material properties of powder-metallurgically produced AMCs compared to the reference materials (Table 1) provide potentials of a better fulfillment of user requirements. Additionally, from the improved yield strength a considerable lightweight construction potential for components made of AMCs can be derived because of reducible material cross-sections. Taking 250 MPa as a reference value of yield strength, 500 MPa (approx. yield strength of powder-metallurgically produced AMCs, Table 1) represents a doubling of the value. Based on a constant component strength, a reduction of the material cross-section by 50%, a corresponding saving of material quantity, as well as weight reduction of 50% are enabled by the usage of powder-metallurgically produced AMCs [5,25]. These potentials might (over-)compensate the disadvantage of a lower elongation. A lower elongation of a material corresponds to a lower reserve of permanent deformation before breakage [5]. The relevance of a lower elongation of the AMC materials depends on the specific application. Achieved improvements of fatigue behavior (Section 3) can also be a potential. However, further investigations on this are necessary. If potentials of improved properties dominate and are perceived by the users, users can be expected to accept higher costs of AMCs and, therefore, higher prices of aircraft components. Section 5 demonstrates calculations of relevant monetary effects.

Analysis and forecast of markets of aluminum alloys and competing materials has to find out which companies act in the markets and how can the competition situation be characterized from the perspective of material manufacturers, aircraft component manufacturers, aircraft manufacturers, and airlines. For this, instruments such as industry analysis, competitor analysis, market structure analysis, techniques for determination of market attractiveness in portfolio analyses, quantitative forecast methods, and, again, instruments of market research are usable [5,26]. A popular instrument for analyzing the competition in an industry is Porter's Five Forces Framework [26]. Here, only some selected, particularly relevant "forces" of the competition are shortly characterized [5]:

- The market potential of the innovative AMC materials can be derived from the potential of the aircraft market. In the year 2016, the biggest aircraft manufacturers Boeing and Airbus delivered in sum 1436 airplanes (1397 in 2015) and achieved sales revenues of €66.6 billion (Airbus) and $94.6 billion (Boeing) [27–30]. Regarding aviation, for example in Germany, a compound annual sales growth rate of 0.9% can be expected for the period 2016–2021 [31]. This implies a large and stable demand of aircrafts, aircraft components, and materials for manufacturing these components. Because of their small number, the *bargaining power of* the aircraft manufacturers, which are potential *buyers* of the components and materials, tends to be high.
- Accordingly, the aircraft industry seems to be attractive market for *potential entrants*. At the same time, *intensity of competitive rivalry* is relatively high and the long development cycles and cost-intensive activities of research and development constitute significant barriers to entry especially for small- and medium-sized companies. Development and introduction of new materials and manufacturing processes into the aircraft industry might need decades. High safety standards have to be considered and are monitored by government agencies. In Europe, for example, the European Aviation Safety Agency (EASA) is responsible for certification of airworthiness of civil aircrafts [32,33].
- Manufacturers of competing or substitute materials or companies which are able to produce and supply AMCs can be identified by means of databases, Internet platforms [34], or classified directories. The *bargaining power* of these companies, as well as *of suppliers* of ingredients might be very different, depending on the specificity of the material, and has to be verified.
- The identification as well as comparative analyses of relevant *substitute materials* is advisable already during the technology analysis and forecast. The findings have to be reflected against the requirements of the users of the materials and should be incorporated in the market analysis and forecast. Major aircraft materials, in addition to aluminum, are, as mentioned, steel, titanium, and composites, such as carbon fiber reinforced plastic, competing with each other, depending on the application. (Polymer matrix) composite materials, such as carbon fiber composites, tend to replace aluminum and other metal materials in the aircraft industry (for example, as the Boeing 787 shows) due to higher strength and stiffness and a lower weight [22,32,35]. However, disadvantages of these composites are especially high material and manufacturing costs, but also further shortcomings such as a lower reparability and recyclability [23,36]. Furthermore, due to achieved weight-reductions and improved material properties some opposite trends such as the usage of aluminum-lithium alloys exist [22,23]. Additionally, metal matrix composites (including particle-reinforced AMCs) are recognized as promising materials [37,38].

Results of technology analysis and forecast (properties of powder-metallurgically produced AMCs) as well as user and market analysis and forecast (especially requirements of high strength and low weight; high market potential in aircraft industries) are a base for technology appraisal.

5. Technology Appraisal

Technology appraisal is intended to evaluate the commercial potential of a new technology such as powder-metallurgically produced AMCs in an early stage. The commercial potential can be understood as the expected extent of achieving sustainable profits (defined as difference of long-term revenues and costs) [3,5,39]. Information regarding the commercial potential can be a base for material and technology selection, for directing research activities towards specific application fields and design alternatives, and for decisions about the continuation or stop of research activities.

Technology appraisal comprises two steps: non-monetary and monetary appraisal of economic effects of development, manufacturing, and usage of a new technology. *Non-monetary appraisal* is applicable for preselection of promising technologies which have to be analyzed in greater detail and monetarily evaluated in the second step. Considering this, efforts of data collection can be limited. For non-monetary appraisal, criteria of the *resource-based view* of strategic management should be considered. According to this approach, resources have to be valuable, rare, costly to imitate, as well as not substitutable, and exploited by the organization for achieving sustained competitive advantages and above-average profits in markets [5,40,41]. Powder-metallurgically produced AMCs basically seem to be suitable for achieving these advantages. The results of the technology analysis (Section 3) show considerable assets of the powder-metallurgically produced AMCs compared to the reference materials. In combination with further properties (e.g., machinability [42], low or moderate costs, recyclability), the material potentially features a certain uniqueness and *rarity*, and a specific *value* for users might be gained from this. The powder-metallurgically produced AMCs are *costly to imitate* by competitors of a company when the explored knowledge regarding the materials and their processing is specific (which is supposed here). Furthermore, it seems to be conceivable that the imitability of the knowledge can be restricted by patents or exclusive contracts with users. However, the market characterizations (Section 4) outline a *substitutability* of materials in the aircraft industry. Whether powder-metallurgically produced AMCs could be substituted or not strongly depends on the further developments in materials research regarding AMCs themselves, as well as competing materials, such as carbon fiber composites. Currently, AMCs are investigated by institutes and companies and there are some positive trends of their use [37,38,43]. Finally, a company's ability to exploit the resources (the AMC materials as well as the specific material- and process-related knowledge) depends on its own costs/payments for the implementation of the innovation, the market volume, the attainable market share and price, as well as the existence of material applications which allow for large industrial scales and experience effects. It is difficult to assess as the following monetary appraisal also indicates. Overall, however, the strategic oriented non-monetary appraisal draws a relatively positive picture of powder-metallurgically produced AMCs' potential of gaining competitive advantages [5].

The *monetary appraisal* has to refer to the costs and revenues (or the corresponding payments) caused by a new technology in its entire life cycle consisting of phases, such as development, manufacturing, usage, and recycling. However, for comparing commercial potentials of powder-metallurgically produced AMCs and reference materials, it is sufficient to evaluate expected differences in costs and revenues which are relevant for decisions about the technologies. Due to a limited data base of relevant development and manufacturing costs, following considerations focus on monetary effects of improved material properties and, therefore, on their (additional) monetary benefit (for an user like an airline which might be willing to pay higher prices for aircrafts and their components). An additional monetary benefit (of usage) can be interpreted as an upper limit for higher costs of development and manufacturing of powder-metallurgically produced AMCs.

For monetary appraisal, a long-term, multiperiod perspective and the usage of dynamic methods of investment appraisal that consider time value of money have to be recommended. Here, the net present value-method is chosen [11,44] for calculating (the positive) monetary effects of weight-reduction. As outlined before, it can be assumed that an increase of 50% in yield strength enables savings in material quantities of approx. 50% and, thus, weight reductions of the same ratio [5,25]. It can be stated that the improved yield strength of the material allows for achieving other user requirements regarding quality (e.g., stability and durability) of a specific aircraft component with a reduced material thickness [25]. In the following, calculations of monetary effects of weight reduction will be demonstrated. Afterwards, some constraints will be outlined.

The two addressed (alternative) effects of weight reduction (of materials, components and, finally, aircrafts) in the usage phase are (i) revenue effects because of higher payloads, and (ii) fuel and corresponding cost-saving effects when payload is the same [45]. Calculations are demonstrated by taking a Boeing 747–400 as an example [5]. This model of aircraft consists of, amongst others, 66,150 kg aluminum [46]. Assuming that 25% of this material can be substituted by the innovative AMCs with 50% less weight, a weight reduction of 8268.75 kg can be achieved. For calculating revenue effects of higher payloads, for civil aircraft industry, the monetary benefit of 1 kg weight saving is estimated as €($)100–500 for the time of material usage [35,47]. In sum, monetary benefit for the whole aircraft amounts to €826,875 (8268.75 kg·€100/kg) up to €4,134,375 (=8268.75 kg·€500/kg). These amounts can be interpreted as net present values if the monetary benefit refers to the entire life cycle of the aircraft (approx. 20–30 years) [48].

Alternatively, fuel and corresponding cost-saving effects can be calculated based on the following data:

- estimated fuel saving [49]:
  airplane (short distance): 117–134 kg kerosene p.a. per kg weight reduction
  airplane (long distance): 172–212 kg kerosene p.a. per kg weight reduction
- 1 kg kerosene = approx. 1.25 L kerosene (density: approx. 0.75–0.84 kg/L [50])
- price of kerosene: €1.50 per gallon/€0.40 per liter (1 gallon = 3.78541 L) [51]

Assuming an average fuel saving of 150 kg kerosene p.a. per kg weight reduction, fuel saving per year amounts to 1,240,312.50 kg (approx. 1,550,390.625 L) of kerosene (=150 kg/kg·8268.75 kg). It results in a cost-saving effect of €620,156.25 p.a. If the life cycle of the aircraft (and its components) spans 20 years, the monetary benefit for an airline company can be calculated as a net present value (using a discount rate of 4% based on a 'weighted average cost of capital' with typical capital structures and interest ratios) [44]:

$$620,156.25 \times \frac{1.04^{20} - 1}{1.04^{20} \times 0.04} = 8,428,125.82$$

This amount (as well as the alternatively calculated values of €826,875–€4,134,375) represents the monetary benefit of weight reduction and can be interpreted as an upper limit for costs of weight reduction (especially additional costs of development and manufacturing of powder-metallurgically produced AMCs compared to development and manufacturing costs of hitherto applied materials). If the monetary benefit exceeds the costs of weight reduction, an airline company would prefer to buy an aircraft with AMC components and would be willing to pay an additional price of max. €8,428,125.82 (average price of a Boeing 747-8 as of January 2018 was about $402.9 million [52]). This calculation implies a price of approx. €1019 (=€8,428,125.82/8268.75 kg) per kg weight reduction (which exceeds the above mentioned range of €($)100–500). It could be derived that the price of 1 kg AMC can be higher by this amount than 2 kg of a hitherto used conventional material. However, it has to be considered that this value includes not only material costs (which are much lower for commercial AMCs) but all switching costs caused by the substitution of the material, such as the costs of development or re-design of components, manufacturing processes, and additional manufacturing costs in the entire value chain (consisting of material manufacturer, aircraft component manufacturer(s), and aircraft manufacturer).

The calculations are faced by some constraints. They are based on uncertain data. Calculated values can change considerably depending on changing assumptions regarding fuel price, discount rate, aircraft life cycle, and flight distance during aircraft life [35,45]. For considering data uncertainty, especially the determination of factors with a strong influence on results, as well as critical values of influencing factors, sensitivity analyses can be conducted [44]. Furthermore, the monetary effects of weight reduction in the phases of development and manufacturing of AMC-components are neglected and only addressed here by the considerations regarding the upper limit for costs of weight reduction; they should be elaborated and analyzed in detail [42]. For example, monetary consequences of a changed geometry of components for aircraft construction could be considered as additional costs of the development and manufacturing phase. Additionally, a reduced material cross-section because of the higher yield strength potentially causes lower material quantities which are needed for producing a specific number of aircraft components [25]. Resulting cost-saving effects regarding the material costs should also be addressed by further analyses.

6. Conclusions

In this paper, the concept of an integrated technology, user, and market analysis and forecast has been presented and applied to the case of particle-reinforced aluminum matrix composites (AMCs) and their usage for manufacturing aircraft components. One the one hand, the results show the technological as well as economic potential of this innovative material. On the other hand, the principal applicability of the concept in early life cycle stages as well as its basic advantage—the "merging" of technological and economic analyses and forecasts—has been demonstrated.

However, there is considerable need for further research and development activities and results: Concerning the technological perspective, the degree of maturity of particle-reinforced aluminum matrix composites (AMCs), and the corresponding manufacturing processes has to be enhanced enabling the transfer into the industrial context. In parallel, especially the economic elements of an integrated technology, user, and market analysis and forecast have to be extended and refined in order to show a more complete picture of the economic potential of AMCs. Finally, the instrument of an integrated technology, user, and market analysis and forecast, itself, has to be further elaborated (e.g., by including more single analyzing and forecasting techniques), applied to further cases, and validated.

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