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Assessment strategies for composite-metal joining technologies – A review

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Abstract

Mixed material constructions, especially composite-metal structures, are widely applied in industry. Today many different joining technologies exist. However, the tools are missing that support decision making for the most suitable technology depending on the desired application. Especially small and medium sized enterprises struggle, due to a lack of know-how and their limited innovation budgets. In this review the existing literature about different joining technologies is discussed and evaluated with attention on comparative studies. Based on the described literature a future assessment strategy for enterprises is outlined and a general procedure of data acquisition is presented.

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Keywords: Composite; Joining Technology; Life Cycle; Assessment Strategy, Ecological Impact

1. Introduction

The application of mixed materials structures, for example the combination of metals and fiber reinforced polymers, in this contribution referred as composites, involves high lightweight potential [1]. The combination of dissimilar materials with different property ranges contains a clear task sharing of the components while enabling an optimized use of materials characteristics. Thus savings of energy and resources are encouraged. However, joining composite components is challenging for manufacturers, since they have to ensure a fiber-fair load transmission. For example small and medium sized enterprises (SME) in the automotive sector are facing the challenge of implementing composite-metal components in order to stay competitive. One point is the selection of the most appropriate joining technique, so that the advantages of composite-metal constructions can be fully exploited in a sustainable manner. Here economic viability of the manufacturing process is crucial as well as the required mechanical strength of the joint. Further ecological and legal regulations require life cycle considerations of the whole product life cycle, from raw material and manufacturing process to recycling.

Thus action has to be taken to support the enterprises in design and manufacturing of composite-metal components. An assistance has to be provide to support the decision making and give action recommendations. Therefore a literature review on previous investigations and evaluation was done. The results reveal that most investigations deal with the mechanical assessment of one joining technique varying several parameters. Only a few studies consider more than one technique, yet no study considers life cycle aspects of joining techniques. Consequently no sufficient assessment strategy is available to support the decision for the best joining technique. Thus there is a need to a quantifiable assessment strategy which bases on experimental data und considers mechanical, economic and environmental aspects.

With the results of the conducted review the structure of an assessment strategy and a procedure for data acquisition is presented: Mechanical tests have to be performed on equal specimens which will be manufactured with different joining technologies to describe the mechanical behavior. Additional a Life Cycle Analysis will be conducted, recording energy and material flow in manufacturing processes and recyclability, using standardized analyzing methods in order to compare their environmental impact.

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2. Outcomes of initial literature review

To obtain a widely ranged literature overview the websites Google Scholar and Science Direct were researched. In Google Scholar the following Boolean expression was used, searching in the whole text: [“fiber composite metal connection” OR “composite joining technology” OR “composite connection technology”] AND [“assessment” OR “evaluation”]. In Science direct the whole text research with previously mentioned Boolean expression resulted in more than 4000 hits, so the research was adjusted as follows: [“composite” AND “metal” AND “join” (in Title, Abstract and Keywords)] AND [“assessment” OR “evaluation” (in all fields)].
Not all found search results are relevant for this work since the following thematic areas are not considered in this review:

- Numerical studies and simulations
- Joining technologies for metal-polymer composites without fiber reinforcement
- Joining technologies for fiber reinforced thermoplastic

The results of the conducted literature research are listed in table 1. The sources are clustered into the following themes: mechanical investigation, quality management, economic and ecologic consideration of manufacturing and Life Cycle Assessment. The research showed that the joining of composite and metal components is a current research topic which is discussed by many institutions and considered from many viewpoints. As a first result of the review the different joining technologies are described regarding their characteristics, advantages, disadvantages and improving parameter modifications.

2.1 Joining Technologies and Concepts

For the joining of thermosetting composite components with metallic components different concepts are used: Adhesive bonding, mechanical fastening or a combination of these mechanisms. The selection of a suitable joining concept firstly depends on the geometrical arrangement of the components. In figure 1 the different arrangements are demonstrated. The overlapping joints, including the single laps (a), the comeld joints (b) and the hybrid penetrative reinforced (HYPER) joints (c) are state of the art and mainly discussed in literature. These joint types are applied in industry and will be focused hereafter. However, only few articles deal with the investigation of frontal joints (d, e) and T-joints (f). So far these concepts are state of the research, because they need additional load transmitting elements like doubler plates, thin titanium layers or embedded inserts. However these joining concepts probably have future relevance and at this point they complete the overview.

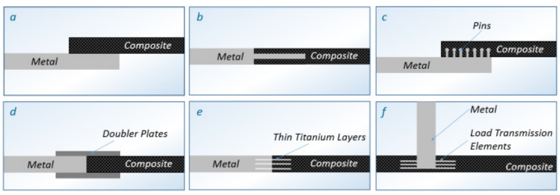

Fig. 1. (a) Single lap joint, (b) Comeld joint, (c) HYPER joint, (d) Frontal joint with doubler plates, (e) Frontal joint with titanium layers, (f) T-joint

2.1.1 Adhesive Bonding

Adhesive bonding is a usually applied concept for the joining of composites components. It is convincing due to the suitability for joining of any combination of similar or dissimilar materials [2]. A distinction is made between traditional bonding of cured components, the bonding of cured components with wet laminates (“co-bonding”) and the bonding of wet laminates (“co-curing“) [3]. Latter method is only applicable for joining composite components with other composite components. Further advantages of adhesive bonding are the flat, uniformly distributed and fiber friendly load introduction. In addition the possibility of bonding components with different thickness. However the material thickness is an important parameter for the overlapping length. Another advantage is the prevention of galvanic corrosion between dissimilar materials. Additionally, adhesive bonding is easier to implement in SME due to the cost efficiency. However the depending of joint durability on adhesive strength must be mentioned, as well as the material degradation over time. The required surface treatments and the long curing time increases the production time and the energy consumption. Further, humidity and temperature requirements necessitate specific attention [2]. To improve the mechanical joint strength sculpted metal components can be used [4].

2.1.2 Through-the-thickness reinforcement

Through-the-thickness reinforcement is based on form locking load transmission, so the stress is introduced over the entire composite thickness. Higher loads can be transferred by the joint due to mechanical interlocking, therefore this method is often used in automotive or aircraft industry. In this work “through-the-thickness reinforcement” is defined as the introduction of joint elements after consolidation in the cured laminate. The drilling of the hole causes a weakening of the fusion zone, fiber damage and an interruption of load transmission [5]. However this injury can be reduced by using vibrational assisted drilling [6]. As for interlocking elements a wide range of features is available. The most widespread options found in industry applications are bolts, rivets and clinches, but also staples with small diameter are investigated by Löbel et al. [7].

Bolt and Rivet joints

Providing high joint strength bolts and rivets are often used for highly stressed engine components. In aerospace industry composite-metal joints usually are connected by titanium rivets, inserted into holes in both materials [8]. The additional advantage of the bolt joining technology is the separating of the connected components by the removal of the joint elements, whereby a subsequent recycling is possible. However the strength and fatigue joint life are influenced by the fiber damage, the yielding polymer matrix in bolted joints and the loss of bolt clamp-up load [9]. Nevertheless the mechanical joint strength can be increased by embedding high strength titanium foils into composite laminate within the fusion zone [10, 11]. A further alternative is the modification with doubler plates or foam inserts [12]. Disadvantages are the high production time and costs for riveting and bolting composites [2], so the economic efficiency of this technology depends on the mechanical requirements of the component.

Table 1. Result of literature review. Scope and appraising to a research theme. A: Mechanical Investigation, B: Quality Management, C: Economic/Ecologic Consideration of Manufacturing, D: Life Cycle

Source	Scope	Theme
Falconieri et al. 2015 [13]	Mechanical testing of the repair of composite joints with titanium inserts. General consideration of repair solutions.	A, C
Kashaev et al. 2015 [8]	Mechanical testing of different composite-titanium rivet joining concepts which are used in aerospace industry in combination with adhesive bonding and surface treatments.	A
Stelzer et al. 2015 [14]	Investigation of fatigue properties of through-the-thickness reinforced joints and comparison to exclusively bonded joints and hybrid penetrative reinforced (HYPER) joints.	A
Wang et al. 2015 [15]	Presentation of a new manufacturing process for the pins in HYPER joints using electronic beam. Mechanical testing and structural monitoring with Digital Image Correlation (DIC).	A, B
Woizeschke et al. 2015 [5]	Investigation of frontal composite-metal joints which uses thin titanium layers for the load transmission.	A
Di Giandomenico 2014 [16]	Tensile testing of adhesively bonded joints. Comparison of different surface features of the metal component and inspection of the joint with DIC.	A, B
Gebhardt et al. 2014 [17]	Experimental evaluation of embedded inserts as integrated mounting points in composite components.	A
Jürgens et al. 2014 [18]	Investigation of an innovative Co-bonding technology for through-the-thickness reinforced joints regarding mechanical behavior. Consideration of cost and time efficient production.	A, C
Lee et al. 2014 [2]	Considerations of the strength requirements of hole-clinching for joining composites with ductile materials and varying the parameters of the tool shape.	A, B
Parks et al. 2014 [19]	Mechanical testing and comparison of HYPER joints regarding pin geometry and surface treatments.	A
Taendl et al. 2014 [20]	Investigation of the electron beam surface structuring for an aluminum alloy in HYPER-joints.	A
Pecat et al. 2014 [6]	Reduction of the material damage on drilling by using vibration assisted drilling.	A
Pejryd et al. 2014 [21]	Damage detection in drilled holes in composite components by Computed Tomography.	A, B
Heimbs et al. 2013 [22]	Investigation of failure behavior of composite T-joints. Comparison of toughened and conventional adhesively bonded joints to through-the-thickness reinforced joints.	A
Löbel et al. 2013 [7]	Comparison of exclusively bonded and purely bolted joints with through-the-thickness reinforced joints using staples as load-bearing elements in combination with bonding.	A
Russo, Zuccarello 2013 [23]	Experimental assessment of co-cured joints regarding mechanical and geometrical parameters.	A
Parks et al. 2012 [24]	Investigation of the HYPER joining technology by additive pin building manufacture. Monitoring of the damage within joints with pulse echo ultrasonic.	A, B
Barroso et al. 2011 [25]	Experimental study of the stress in composite-metal joints which is induced by different thermal expansion coefficients.	A, B
Deng et al. 2011 [26]	Investigation of guided waves propagation in bonded composite components with tapered adhesive layer.	B
Fleischmann et al. 2011 [27]	Investigation of pin manufacturing process for HYPER joints using an arc welding process. Comparison of different pin geometries and mechanical testing of the joint strength.	A
Friedrich et al. 2011 [28]	Damage detection with electrical resistance measurement using inherent CNTs in composite in bolted joints.	A, B
Raykhere et al. 2010 [29]	Dynamic testing of adhesively bonded composite-metal joints regarding shear strength.	A
Ucsnik et al. 2010 [30]	Investigation of HYPER joining technology using small metal spikes regarding mechanical failure behavior and reproducibility and comparison with epoxy bonded references.	A
Caccese et al. 2009 [9]	Experimental investigation of stress relaxation on clamp-up load in bolted composite-metal joints and comparison of different bolt types.	A
Fink et al. 2009 [10]	Mechanical investigation of bolted joints with embedded titanium foils in the fusion zone for the load transmission.	A, (C)
Kolesnikov et al. 2008 [11]	Investigation of embedded thin titanium layers in bolted composite-metal joints.	A
Young Chen 2007 [31]	Nondestructive evaluation of adhesively bonded composite joints. Improvement of accuracy of crack detection by waveguides.	B
Kabche et al. 2006 [12]	Mechanical investigation of composite-metal bolted joints and comparison of different modifications with foam inserts and doubler plates.	A

Hole-clinching

Hole-clinching is a suitable process for joining brittle materials such as composites with ductile metallic materials. This technology provides a geometrical interlocking whilst no additional joining elements are required. Thus the production time and costs are reduced in comparison to other mechanical methods [2]. Hence the clinching technology, especially for less stressed structures and mass production is easy to implement in SME. Disadvantages are the high introduced loads, so fiber damage of the composite substrate and residual stress in the metal component cannot be avoided. Further the separating of connected components is difficult, which makes the recycling of clinched components challenging.

To improve mechanical stability, water tightness and corrosion resistance of bolted and riveted joints adhesive bonding is used additionally.

2.1.3 Hybrid penetrative reinforcement (HYPER)

In opposite to previously described bolted, riveted and clinched composite-metal joints, HYPER joints use integrated joint elements. Hence it contains small pins, upsetted on the surface of the metallic component which are integrated in the uncured composite substrate. This provides a mechanical interlocking and additional epoxy adhesion around the pins and the level surface of the metal component [19]. The HYPER technology is time and cost-intensive, due to the requirement of special tools and know-how. In literature different concepts of pin building are described, which includes additive and subtractive manufacturing processes. Additive manufacturing is advantageous compared with traditional subtractive manufacturing due to a more efficient use of material. A further method is the attachment of pre-fabricated pins by cold metal transfer (CMT), which is easy to implement in SME due to its cost efficiency [19]. As a recent method electron beam surface treatment for forming protrusions was developed by Wang et al. [15].

To integrate the metallic pins in composite substrate different processes are used. One option is the Resin Transfer Moulding (RTM), which is consecutively laying dry ply onto metallic substrate with subsequent resin injection. Another possibility is the use of a pre-impregnated substrate and pressing the pins into the uncured laminate with an ultrasonic horn and following consolidation in an autoclave [19].

Main advantage of HYPER technology is the positive mechanical failure behavior comparing to other joining methods which was investigated e.g. by Ucsnik et al. [30]. Detriments are the elaborated manufacturing process and the difficult separating and recycling of the components.

2.1.4 Embedded Inserts

For thin-walled composite components usually metallic inserts are used consisting of a thin metal sheet which is embedded between the laminate plies in RTM-process or with the hand lay-up technique [17]. A threaded bolt introduces the load through the thin metal sheet into the composite laminate. To increase the joint strength, bead patterns or surface treatments on the metal sheet are used [17]. Advantages of using embedded inserts are the fiber friendly load transmission and the possible optimization of fiber orientation in the fusion zone. Further benefit is the easy separation of the metal component regarding recycling aspects. Disadvantageous is the time and cost-intensive fabrication. Nevertheless insert manufacturing costs can be reduced by the welding of standard parts. A further drawback, applying to all mechanical joints – bolts, rivets, clinches, pins and inserts – is the elaborate visually damage detection [28]. Though Pejryd et al. found that the damage in surrounding material can be detected by computed tomography [21].

2.2 Scope of previous considerations

As mentioned above the different joining technologies are considered from many viewpoints. However aspects regarding Life Cycle Analysis are not considered. The main focus in literature is the mechanical behavior of the joints, especially strength requirements and the evaluation of the fatigue failure behavior. Most articles, e.g. Parks et al., deal with the investigation of one joining technology with the variation of diverse geometrical and processual parameters [19]. Only a few articles deal with the comparison of several joining technologies regarding mechanical joint strength such as Löbel et al. or Stelzer et al. [7, 14] Nevertheless the comparison of more than two joining technologies has not been done so far. Furthermore joint inspection methods for damage detection are discussed in literature, which enables an evaluation of the joint quality. In contrast to the detailed consideration of the just mentioned themes, the following aspects are rarely to be found in literature: optimization of the manufacturing process, such as Lee et al. and the investigation of damage reduction in composite substrate [2]. Furthermore specific investigations of the manufacturing process regarding time, costs, material or energy flow and recycling possibilities could not be found. To sum up, no quantifiable comparison of the different composite-metal joining technologies regarding mechanic, economic and ecologic aspects is possible. Therefore new approaches to close this research gap have to be generated.

3. Approach for closing the research gap

To support the enterprises, especially SME in the selection of suitable joining technologies for composite-metal constructions, a decision tool has to be developed. For this reason the limitations and possible structures of the assessment strategies are presented in the following.

3.1 Limitation and structure

First the scope of the assessment strategy has to be limited in order to allow a comparison. Therefore exclusively thermosetting materials will be reflected in preliminary considerations due to the higher industry application range. Therefore welding methods which are used for thermoplastic materials will not be considered. In concrete experimental investigations on one specific material combination, e.g. carbon fiber/epoxy and titanium will be done. Furthermore only an overlapping arrangement of components will be considered, based on the previously restricted range of joining technologies: adhesive bonding, bolt, rivet and HYPER joining and the application of embedded inserts. Using this restriction and varying only the most promising modifications clear statements can be made. As part of the assessment an evaluation of the possibility to transfer the obtained results to other material combinations is conducted. Thus generalized action recommendations could be given.

For the assessment of the joining technologies decision pathways, structured in thematic areas, have to be generated (ref. in figure 2). The main attention is focused on the mechanical strength requirements of the joint, due to essential function fulfillment. At this point the bearable stress level is important as the type of stress e.g. dynamic or static loading, tension, bending, torsion, fatigue behavior and loss of clamp load. Subsequently, the quantities which should be produced and the available manufacturing tools guide the following decision. So the joining technology depends on the process. Last but not least the separation and recycling possibility of the components have to be considered, too. In the manufacturing, as well as in recycling decisions the economic viability and ecological impact of the joining technologies in the entire product life cycle are essential. So the economic evaluation criteria have to include tool and material costs, energy consumption in all needed processes, labor costs for know-how, manual work and the manufacturing time. Whereas the ecologic criteria consist of the material flow from raw material to remanufacturing, recycling or disposal. Furthermore the legal regulations regarding carbon dioxide emissions have to be considered. Therefore the whole product life cycle is considered, in order to driven a definitive statement about the most suitable joining technology for the reflected application.

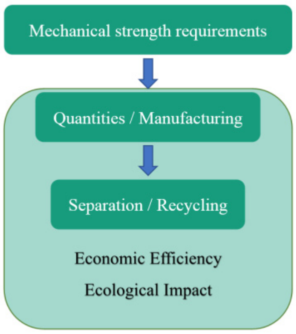

Fig. 2. Structure of an assessment strategy

3.2 *Data acquisition*

The assessment strategy, the approach generated in this work, must be based on experimental data and thus providing meaningful and significant action recommendations for enterprises. Therefore the needed numbers will be bought, if possible. Otherwise standard tests will be defined according to statistical design of experiments. The specimen first will be analyzed on mechanical criteria which are relevant for the fracture behavior of the joints. Aim of the mechanical investigations is the quantifiable comparison of industrial applied joining technologies. The most important criteria are the static and dynamic strength. The static joint strength will be investigated by tensile tests according to ISO 527-4 and flexure tests according to ISO 14125. The investigation of the joint strength regarding cycling loading will be performed with fatigue tests according ISO 13003. Further the bearing response of the composite substrate of joining technologies using load transmission elements will be tested according to ISO 12815. The mentioned standardized tests are selected due to their relevance in past investigations and the industrial application.

Life Cycle Assessment

In addition to the mechanical investigations, data for quantifiable statements about the economic viability and the ecological impact have to be purchased. Thus a Life Cycle Assessment (LCA) according to ISO 14040 will be made. The obtained results will be used as input to a variety of decision-making processes for the assessment strategy generated in this work [32]. LCA studies consist of four phases, seen in figure 3 [32].

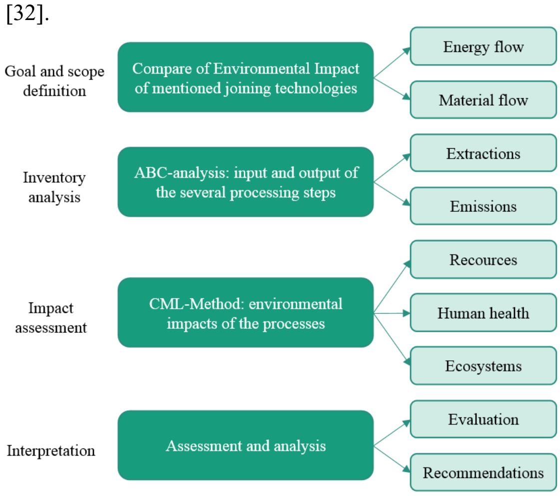

Fig. 3. Procedure of a Life Cycle Assessment

First phase will be the goal and scope definition which includes the comparison of the environmental impact of the joining technologies. The measurement and recording of the energy and material flow provides data to assess on the one side the ecologic impact, but on the other side also the economic viability. The second phase is the inventory analysis which will be implemented with a widely industrial used ABC analysis [33]. For this purpose the input and output of the several processing steps will be recorded. Moreover the raw material extractions and the emissions such as carbon dioxide, will be considered. To assess the impact of these extractions and emissions, the CML method is used which was developed by the Centrum voor Milieukunde of the University Leiden in the Netherlands. The CML method is a suitable technique for this work due to the consideration of important material and energetic exchange relationships and their quantifiable evaluation [34]. In this phase previous obtained data from the ABC analysis will be investigated on their impact of different characterization categories such as the global warming potential. In the last step of the LCA the achieved results will be interpreted and recommendations will be elaborated. In this way a comprehensive comparison of the joining technologies will be possible.

4. Conclusion

The systematic review has explored, that no sufficient comparison of the different joining technologies for the connection of composite and metal components exist in literature. Investigations mainly refer to mechanical aspects rather than economical ones. Latter is considered in a few articles qualitatively, but not in a quantifiable comparison of economic values. Moreover ecologic aspects and Life Cycle Analysis are not considered in literature at all. Thus no sufficient data exist for the selection of a suitable joining technique for composite-metal joints in order to give recommendations for composite implementing enterprises.

There is a need for an assessment strategy to support enterprises in manufacturing of composite-metal structures in mechanical, economical and sustainable manner. Based on the conducted review the outline for future research is presented. The assessment strategy must base on experimental data to give quantifiable action recommendations, whereby these crucial data have to be purchased with standardized tests to assure the comparability. In order to reach this aim mechanical tests will be made to describe the strength and fracture behavior. Furthermore a Life Cycle Assessment will provide information of the financial burden for enterprises and the environmental impact on the involved manufacturing processes.

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