Material Property Modification of Continuous Fibre-reinforced Aluminium Matrices Produced by Semi-solid Forming Strategies

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Abstract
Targeting lightweight concepts, research activities in the fields of automotive engineering, aerospace engineering as well as civil engineering are focusing on the development of high-strength and high-rigidity composite materials. Such composites are to be used where properties of conventional materials are not able to withstand the constantly increasing demands of industrial applications. In this context, the Institute for Metal Forming Technology/Stuttgart is concerned with the development of new processes for the manufacturing of metal matrix composites utilizing semi-solid forming strategies. Thereby, the objective target is the infiltration of continuous reinforcing components like carbon or glass fibres by aluminium matrix materials.

Keywords: *Semi-solid forming, Metal matrix composites, Material characterization, Tool design*

1 Introduction

Current research activities concerning metal matrix composite (MMC) applications are predominantly focusing on metal alloys with integrated discontinuous reinforcements, like short fibres, particles or even nanoparticles, and on the corresponding processing technologies. In these processes, developed in a multitude of past research activities, metals are used in the liquid, the solid (powder metallurgy) and even the semi-solid state [1-6]. Thereby, discontinuous reinforcements were preferred over continuous reinforcements like fibres or filaments made of glass, carbon or ceramic, because of their easier handling, the lower production costs and the almost isotropic properties.

However, as through the combination of continuous fibrous reinforcing materials with light metal matrices highest performances or rather highest strengths can be achieved, research work is also focusing on producing metal matrix composites reinforced in this way [7-11]. The processes investigated in this context principally are using metallic matrix materials in the liquid state. Thereby, the most significant disadvantages are the high process temperatures and the long process durations, which lead to a damaging of the fibres used. An approach to reduce such a fibre damaging during the manufacturing process is using semi-solid forming strategies.

In this context, previous research projects conducted at the Institute for Metal Forming Technology already emphasized the high potential of metal matrix composites (MMC) produced by such semi-solid forming technologies [12-13]. They described thixocasting processes for manufacturing fibre-reinforced MMC components by the usage of prepregs, consisting of laminated woven carbon fibres, and aluminium sheets or thermally sprayed metal coatings. Within further investigations, the manufacturability of such semi-solid formed MMC components was proved, and first results concerning the interaction of used materials with regard to adjusted process parameters and achievable component properties were provided [14].

Based on these research activities, the Institute for Metal Forming Technology is still carrying out research work in the field of manufacturing metal matrix composites by semi-solid forming strategies, whereby one of the basic objectives is the integration of reinforcing components in the form of different fibrous materials into aluminium matrices.

One of the current research projects conducted in this context is entitled “Hybrid Intelligent Construction

Elements" (HIKE). It is supported by the German Research Foundation within the framework of the DFG research group FOR 981 since 2009 and is carried out jointly together with six other institutes belonging to the University of Stuttgart.

The objective of the sub-project undertaken at the Institute for Metal Forming Technology contains manufacturing of hybrid and adaptive lever elements by semi-solid forming. These elements consist of specified combinations of different materials integrated into lightweight metal matrices. By means of such constitutive and structural material combinations, higher degrees of lightweight materials are to be developed for producing structural elements customized to its application profiles by intrinsic property modifications [15-16].

The investigations reported about in this paper were conducted within the framework of a work package belonging to this research project, focusing on the manufacturing of aluminium matrices reinforced by continuous carbon, glass, ceramic and basalt fibres, and on the attainable material properties, in particular tensile strengths and Young´s moduli. The forming tool used for these investigations was designed in the course of a research project, which is described in the following.

This project is titled "Material-compatible joining of composite profiles" (MaFüFa) and deals with the development of material-specific joining technologies concerning fibre composite profiles, by implementing a transition from polymer to metal matrices at the intersection of the load introduction. The research work is conducted in cooperation with the Institute for Lightweight Structures and Conceptual Design (ILEK) and is funded by the Research Initiative "ZukunftBAU" of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (document number: SF-10.08.18.7-10.22/II 3-F20-10-1-054).

Essential target of the project is the application of the semi-solid forming process for a partial impregnation of glass and carbon fibre bundles with light metal matrix materials, without significantly affecting the fibres´ properties. After the forming process, conducted at temperature levels of 580°C and above, the exposed fibre portion subsequently will be embedded in a polymer matrix, whereby a transition between the used matrix materials is to be realized.

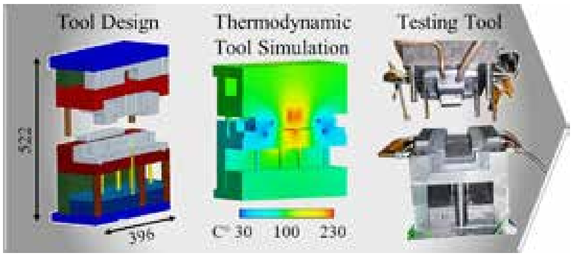

Figure 1: Design, simulation and manufacturing of the "MaFüFa"- testing tool.

In this context, a fibre composite material with a reinforcing metallic matrix in the area of the load application is to be produced. This allows usage of joining technologies like bolting and welding, whereby the advantages of composite materials, such as weather resistance, high load capacity, low thermal conductivity and low density, are extended by benefits of structural metal constructions, such as its good joinability and recyclability [17-18].

2 Tool Design and Forming Process

In the framework of the research project "MaFüFa", a novel testing tool for plate-shaped test components was designed, simulated and subsequently manufactured (cf. Figure 1). The tool is equipped with an open cavity ensuring the required fixation of fibres applied in the form of rovings. Furthermore, it enables the partial infiltration of continuous reinforcing fibres by matrix materials.

Because of the open tool cavity and the associated discharge of semi-solid material, generating the high internal pressure required for the fibres´ infiltration is difficult. Therefore, the tool has to possess different temperature ranges, as depicted in the middle picture of Figure 1, to effectuate a specific solidification and, thereby, a self-locking of the matrix material. For this reason, the outer parts of the segmented cavity are equipped with a cooling system. The matrix material, initially filled into the heated centre of the lower cavity, solidifies by encountering these chilled parts. Additionally, the solidification of the material is supported by the spring-loaded and also chilled outer punch elements, which are used for closing the cavity except for a small gap. Thereby, the material´s discharge is prevented and the prestressed fibres are guided, before initiating

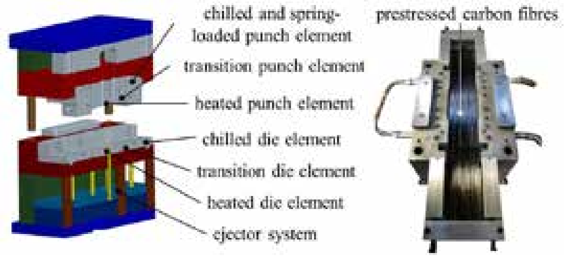

Figure 2: Tool design and prestressed carbon fibres in the lower tool half.

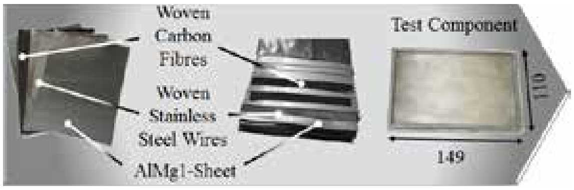

Figure 3: Layered semi-finished material and finally formed plate-shaped test specimen.

material flow to avoid its displacement. Despite the open tool cavity, this tool design enables the application of sufficient internal pressures for satisfying infiltrations of fibrous reinforcing materials.

Figure 2 illustrates the design of the forming tool and the arrangement of the single cavity elements. Furthermore, it shows a picture of prestressed carbon fibres clamped into the lower tool half by a custom-built device.

After clamping the reinforcing fibres, a piece of the aluminium alloy AlSi7Mg0,3 defined as matrix material according to several preliminary tests is heated up to the liquid state. In this manner, the prestressed fibres are partially pre-infiltrated by pouring the material into the cavity. During this manual pouring, the liquid alloy cools down, passes into the semi-solid state and, thus, ensures a good cavity filling by laminar flow characteristics when carrying out the subsequent forming process. In this process, the punch displaces the matrix material, which fills the cavity´s volume up to the chilled punch and die elements, whereby the self-locking solidification of the aluminium occurs.

The conducted forming trials have shown that a good infiltration of fibrous reinforcing components by using semi-solid aluminium alloys depends on several process parameters. Here, the most important ones are the heating of the matrix materials, the tool temperature, the velocity profile of the press ram and the clamping effect of the fibres.

When clamping the fibres into the forming tool, it is important to ensure that the individual rovings sustain a sufficient distance between each other, in order to permit the matrix material to completely pre-infiltrate the fibres during the pouring process. Furthermore, it is necessary to assure, that the fibres neither are stressed too tight nor too weak prior to pouring. A strong fibre tension may cause the matrix material not to penetrate between the individual filaments of the rovings when conducting the forming process. In contrast, a weak tension leads to disadvantageous displacement of fibres because of the low resistance against the high loadings occurring during the cavity filling process of the semi-solid material.

3 Results and Discussion

Within the framework of earlier investigations on the manufacturability of metal matrix composites with continuous reinforcements by using the semi-solid forming process, plate-shaped components with a length of 149 mm, a width of 110 mm and a thickness of 7 mm were generated. In this process, the matrix and the reinforcing materials were arranged as layered semi-finished material as depicted in Figure 3 and heated by an infrared oven. AlMg1 (EN AW-5005) wrought aluminium rolled sheets (s=0.280mm) were chosen as matrix material, whose mechanical properties were specifically changed by introducing woven carbon fibres and woven stainless steel wires (1.4301) [12,14,16,19].

For conducting uniaxial tensile tests, flat bar tension specimen according to DIN 50 125 with a thickness of 4 mm, a width of 10 mm and a basic measuring length of 35 mm were machined from the plate-shaped test components. Furthermore, samples for metallographic examinations were produced. Figure 4 shows a cross-section of one of these samples taken by a light-microscope as well as results of the tensile tests.

As depicted, the laminate configuration and the orientation of the characterizing components are maintained and can be clearly discerned. The aluminium matrix penetrated the woven carbon fibres very well and the individual fibre filaments are completely embedded.

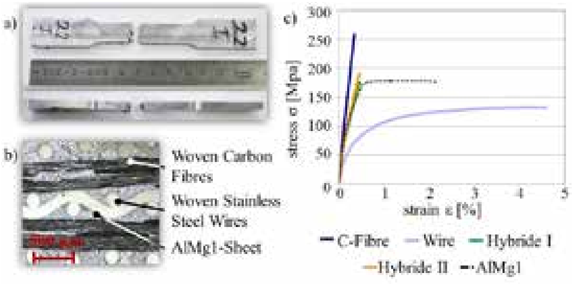

Figure 4: (a) Tensile specimen DIN 50125. (b) Cross-section of a produced test component. (c) Stress-strain diagram of the investigated composite and matrix materials.

The diagram shows that, by using the corresponding values of the matrix alloy as a reference, the achieved mechanical properties of the carbon reinforced matrix exhibit an increase in tensile strength by 45% and a decrease in fracture strain by 84%. By using woven steel wires as sole reinforcing, the fracture strains of non-reinforced AlMg1 specimens were more than doubled, however, in conjunction with a decline of the tensile strength by 26%. By utilizing both carbon fibres and steel wires (cf. Hybrid I and Hybrid II), as depicted in the just mentioned cross-section, no significant improvement of mechanical properties has been noted [20].

The layered structure of the semi-finished material and the usage of a special tool design ensure short flow distances of the matrix material and high internal pressures in the tool´s cavity. Thus, high fibre infiltration within the manufactured components has been achieved and high contents of fibres up to 25% could be realized. However, the disadvantage of this process is the deficient fixation of the layers resulting in a displacement of fibres during the forming process. For this reason, the reinforcing components cannot be aligned in the expected direction of loading, despite the correct orientation of the fibres within the produced components is of immense importance for their resulting reinforcing effect.

For this reason, the novel testing tool for manufacturing plate-shaped test components described in *2 Tool design and forming process* was designed at the Institute for Metal Forming Technology enabling the partial infiltration of continuous reinforcing fibres by matrix materials. The tool is equipped with an open cavity ensuring the required fixation of fibres applied

Figure 5: MMC plate with exposed continuous carbon fibres.

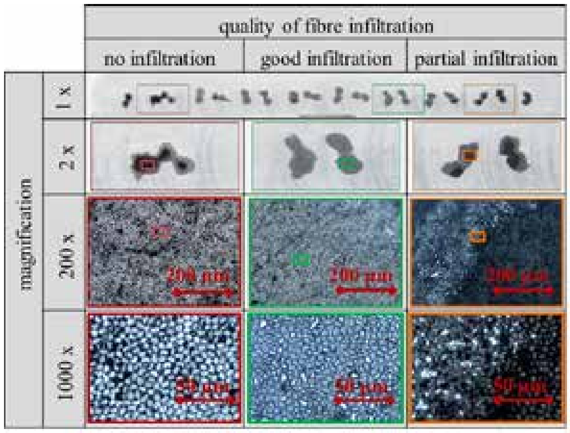

Figure 6: Quality levels of fibre infiltration (AlSi7Mg0,3-matrix + carbon fibre bundles).

in the form of rovings. The results of experiments for determining mechanical properties of metal matrix composites reinforced by carbon, glass, ceramic and basalt fibres are discussed in the following. Figure 5 shows one of the components with exposed carbon fibres produced in this context.

As a high-quality infiltration of fibrous reinforcing materials is of significant importance for attainable mechanical properties of metal matrix composites, very simplified assessments of the components´ quality were conducted during the forming tests performed for determining optimal processing parameters. Thereby, the produced components were vertically cut and the resulting cut surfaces subsequently sanded wet with fine abrasive paper.

After wet sanding, some fibre bundles showed bright grey colorations and some of them darker black areas, as depicted in Figure 6. Metallographic investigations on the cross sections revealed that the grey coloured fibre bundles were completely infiltrated by matrix material, whereas analysis of the black areas showed no or rather poor fibre infiltrations as illustrated below.

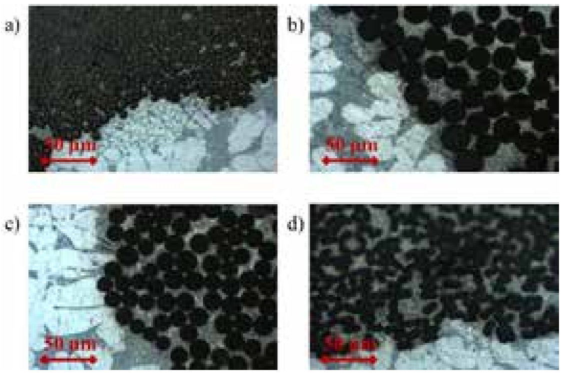

Figure 7: Micro sections (1000x) of AlSi7Mg0,3-matrices reinforced by a) carbon fibres (filament Ø: 7µm), b) glass fibres (Ø: 17µm), c) basalt fibres (Ø: 17µm) and d) ceramic fibres (Ø: 11µm).

This very simple visual analysis of the fibres´ infiltration quality enabled quite rapid evaluations of components manufactured during the forming tests, without requiring extensive metallographic examinations. These tests showed that the quality of fibre infiltrations and, thus, the attainable mechanical properties of produced components were influenced by different processing parameters to varying degrees. These parameters are material heating, material filling, tool temperature, velocity profile of ram and fixation of the fibres.

After determining optimum settings for manufacturing AlSi7Mg0,3 matrices reinforced by continuous carbon fibres, it was also possible to achieve good infiltrations for fibres made of glass, basalt and ceramic by using the same parameters. In this context, Figure 7 shows micro sections of well infiltrated fibre rovings and non-reinforced metal matrix areas.

Upon closer examination, the microscopic images reveal a non-uniform distribution of the aluminium matrices´ liquid phase, which can be identified between the single fibre filaments, and the diphase region of non-reinforced areas having very coarse-grained microstructures. During tensile tests conducted within the framework of the research work and presented in the following section, in particular, the very brittle fracture behaviour of these casting structures led to a reduction of material´s elongation and therefore to a decrease of achievable strength values. However, these tests also provided satisfying mechanical properties

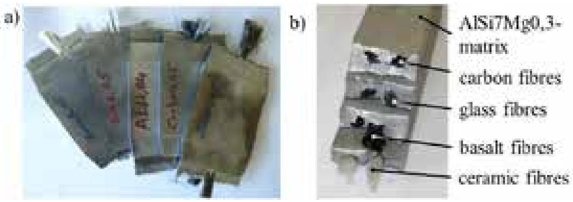

Figure 8: a) Components for manufacturing flat bar tension specimens after DIN 50 125. b) Fracture surfaces of tensile specimens with different reinforcing fibres.

of produced components for low elongation levels, which, in principle, is proof for good adhesion between infiltrated fibres and metal matrix.

Figure 8 a) shows components used for manufacturing flat bar tension specimens according to DIN 50 125. Thereby, two fibre bundles were integrated right into the middle of each plate, ensuring equal fibre positions and fibre volume ratios within the single specimens. As at the current state of research it is possible to realize satisfying fibre infiltration qualities for a maximum fibre ratio of only 13%, this value was also transferred to the tensile tests. The positioning of integrated fibre bundles can be seen in Figure 8 b), which shows fracture surfaces of tensile specimens reinforced with different fibre materials. Material properties of the different fibres are given in Table 1.

Table 1: Technical data of the investigated fibre materials

	carbon fibres	**glass fibres**	**basalt fibres**	**ceramic fibres**
manufacturer	SGL Group	Owens Corning	Kamenny Vek	3M
product designation	SIGRAFIL C	X-Strand S	BASFIBRE	NEXTEL 610
tensile strength R_m [N/mm^2]	4.000	5.110	4.000	2.930
Young´s modulus E [N/mm^2]	230.000	88.000	92.000	373.000
diameter of filaments [mm]	0,007	0,017	0,017	0,011
fibre volume ratio [%]	12,83	13,06	11,99	12,82

While fracture surfaces of MMC specimen with carbon, glass and basalt fibre reinforcements predominantly showed brittle failure behaviour and,

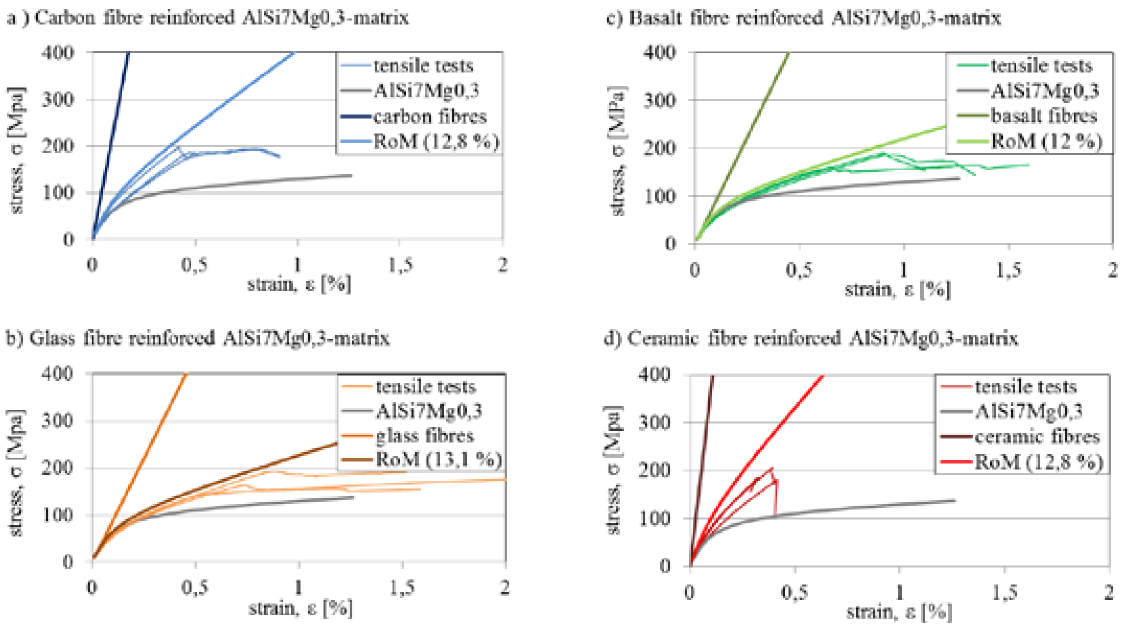

Figure 9: Stress-strain diagrams determined by tensile tests of AlSi7Mg0,3-matrices reinforced by a) carbon fibres, b) glass fibres c) basalt fibres and d) ceramic fibres.

occasionally, an extraction of single fibre filaments, most tensile tests of aluminium matrices reinforced with ceramic fibres caused pull-outs of complete fibre bundles. Such fibre pull-outs indicate a poor interface adhesion between fibre and matrix materials, which is also confirmed by the abruptly ending stress-strain curves of the ceramic fibre reinforced tensile specimen depicted in diagram d) of Figure 9.

Within each of these diagrams, three resulting curves of the tensile tests (thin curves), the stress-strain curve of a non-reinforced aluminium matrix, as reference (grey curve), the idealized curve of the relevant fibre material (linear-elastic) and a curve titled “RoM (fibre volume ratio in %)” are demonstrated. This “RoM-curve” was calculated by combining values of the non-reinforced aluminium matrix and of the idealized fibre material using the so called “Rule of Mixture” [14,21,22]:

$$R_{m\ comp.} = R_{m\ fibre} \cdot V_{fibre} + R_{m\ matrix} \cdot V_{matrix} \quad (1)$$

In this way, strength values determined by conducted tensile tests could be compared to the theoretically attainable values of ideal metal matrix composites with relevant fibre contents.

Even though the tensile tests showed very low fracture strains, the stress-strain curves of samples reinforced by carbon, glass and basalt fibres in most cases revealed good correlations with the theoretically calculated values. Thereby, the values of glass and basalt fibre reinforced matrices concurred at an accuracy of about 90% and the values of carbon fibre reinforced matrices of about 80%, which indicates an excellent quality of fibre infiltrations as well as good adhesion between fibre and matrix materials.

Furthermore, the fibre volume ratios of about 13% caused an increase of tensile strength of aluminium matrices by ca. 10-12% using glass and basalt fibres as reinforcements, by ca. 15% using ceramic fibres and by ca. 20% using carbon fibres. Additionally, ceramic fibres increased the Young´s modulus by ca. 17% and carbon fibres by ca. 22%. Glass and basalt fibres only caused negligible modification of elasticity.

On the one hand, the results presented substantiate the feasibility of metal matrix composites with varying reinforcing materials using semi-solid technologies and, on the other hand, indicate the processes potential concerning defined modifications of material properties.

4 Conclusions

By means of the current research work reported about in this paper, it was possible to modify mechanical properties of aluminium alloys by integrating different continuous fibre materials into work pieces´ volumes using the semi-solid forming technology. In this context, forming tests were conducted at the Institute of Metal Forming Technology (IFU)/Stuttgart for investigating the integration of woven reinforcing fibres and fibres in the form of rovings into aluminium matrices.

Especially material investigations on carbon, glass and basalt fibre reinforced aluminium matrices, consisting of metallographic examinations and tensile tests, indicated satisfying infiltration qualities as well as good adhesion between fibre and matrix materials. For low elongation levels, the mechanical properties of components manufactured within the framework of the forming tests even nearly reached theoretically attainable values calculated by the "Rule of Mixture".

Based on these results, future research work will focus on aluminium matrix materials having higher elongations at break, even after casting processes, and on heat treatments realizing more ductile material properties for better exploiting fibre materials´ properties. Furthermore, more detailed metallographic investigations such as scanning electron microscopy (SEM) will be conducted in order to better understand interface reactions between fibre and matrix materials.

Acknowledgments

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