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Materials Selection Process for Compound-Extruded Aluminium Matrix Composites**

By *Kay André Weidenmann, Claudia Fleck, Volker Schulze, Detlef Löhe**

Today, the design of load-bearing structures of the majority of transportation systems such as automobile structures, aircraft space-frames, railway carriages or ropeway cars is focussed on lightweight constructions providing several advantages. Lower weight reduces fuel consumption, increases the payload and facilitates additional desired functions. Compound extrusion is a rediscovered process representing a promising technique for the production of unidirectionally-reinforced lightweight profiles which may be utilized for structural components.[1] The process itself was invented in the 1970s to produce conductor rails for subway systems.[2] The main focus was put on the functional aspects of the compound. The aluminium profile offers excellent electric conductivity reducing the electric loss and, in addition, in-situ cladded steel ribbons decrease wear effects while operating. As a further benefit, the metallurgical bond between aluminium and steel evolving due to the high pressure and high temperature during compound extrusion made redundant traditional mechanical joining methods.[3] This material combination proved to be technically workable and has therefore been a starting point for further examinations.

The Transregional Collaborative Research Centre SFB/TR10 engages in research on integration of forming, cutting and joining for the flexible production of lightweight structures with an emphasis on compound extrusion. In contrast to conventional casting methods for the production of composites, compound extrusion is a near-net-shape process allowing for the rapid and flexible in-line production of unidirectionally-reinforced profiles. In comparison to particle or short fibre reinforced profiles the position of unidirectionally-oriented reinforcing elements can be adjusted to the internal load distribution of the profiles.

Regarding the compound extrusion of such reinforced lightweight profiles for structural applications, no other materials combination has yet been systematically assessed or examined since the investigations on compound conductor rails, nor have such profiles been industrially produced by the aforementioned process. On this account, no information on further possible materials combinations is available in open literature. Insofar, a systematic materials selection process particularly respecting the compound extrusion demands is mandatory.

Of utmost interest, when designing compounds for the use in vehicles, is the weight reduction of the overall structure by optimising the shape and by using low-density materials in combination with the optimum number of reinforcing elements. This may be accomplished by increasing the strength and the stiffness, while the ductility should not decrease substantially.[4] However, the selection of two different materials with each having distinct characteristic properties raises difficulties that have to be considered if the composite ought to be functional. In this regard, residual stresses due to different thermal expansion coefficients should be mentioned[5] as well as the risk of corrosion as a result of different electrochemical potentials.[6]

Basic studies on the mechanical behaviour of potential reinforcing elements and metallographic images are the first steps of the upcoming investigations.

Process requirements for compound extrusion: Disregarding the fabrication technique used, the above-mentioned issues need to be addressed for all kinds of metal matrix composites. When utilizing the compound extrusion process, a number of additional requirements regarding both the matrix material and the reinforcement material need to be considered. While conventional casting methods as state of the art techniques for the production of composites essentially require good castability of the matrix material in the molten state, compound extrusion like rod extrusion depends on sufficient extrudability of the matrix material. As high temperatures reduce the die life substantially, the extrusion temperature should not exceed 500 °C, at which hot working steels may still perform satisfactorily. This rationale evidently demands for a low melting point material as matrix, entailing the selection of a material of prominent extrudability, even at reduced extrusion pressures.[7] Suitable matrix materials, meeting the extrusion process requirements, are readily available. In the course of materials selection, attention was paid to differences in the material's extrudability as a function particularly of the melting temperature region, the character and content of alloying elements, and the size of precipitations or inclusions.[7]

Regarding the reinforcing elements, the main focus was drawn on maximum tensile strength of the incorporated unidirectional component, which allows for embedding the reinforcing elements into the matrix without major damage to the element itself. Figure 1 schematically depicts a hydraulic extrusion press as modified for the compound extrusion process.

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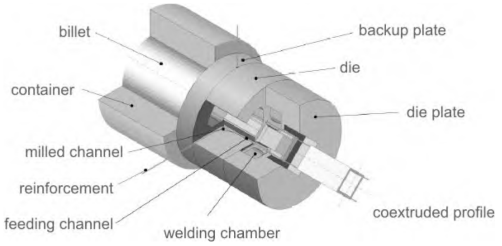

Fig. 1. Schematic diagram of a compound extrusion press. [8]

The reinforcing element is continuously fed into the press in an angle of 90° or alternatively 180° implicating a defined bending of the reinforcing element in a constructively confined zone. Therefore, the bending radius has to be sufficiently large as to avoid plastic deformation of the reinforcing element. The maximum bending stress $\sigma_{\max}$ of a circular-shaped wire as the reinforcing element with the diameter d and Young's modulus E, bent around a cylindrical drum with the diameter 2R, is given by Timoshenko[9] as

$$\sigma_{\max} = \frac{Ed}{2R+d}\,. \tag{1}$$

With the bending radius R given by the particular design of the compound extrusion press, the parameters remaining variable for the reinforcing element are:

the Young's modulus E, the yield stress σ_y, which ought to be larger than $\sigma_{\max}$ avoiding plastic deformation of the reinforcing element; the diameter d, which has to fulfil two contradictory requirements. First, a smaller diameter reduces the maximum bending stress, which the reinforcing element has to withstand while being conveyed within the press. Secondly, with increasing diameters, the maximum load that can be tolerated at the tensile strength is increased both in the final compound and during the incorporation of the reinforcing element.

These requirements have to be met at the respective extrusion temperature also demanding for a high tensile strength of the reinforcing element at elevated temperatures.

Materials selection process. Matrix material: As abovementioned, lightweight profiles require a low-density matrix material such as the light metals. While the specific modulus (E/ρ) and strength (σ/ρ) of aluminium, for instance, under tensile load are comparable to the properties of steels, respectively, light metals outperform steels under inhomogeneous loads like bending or torsion. Especially, aluminium and magnesium alloys are state-of-the-art materials for rod extrusion. Extrusion of titanium and its alloys, however, requires high temperatures and thus is still a niche process for such profiles.[7]

As the extrusion of magnesium alloys requires careful temperature control, owing to the complex deformation mechanisms in the hexagonal lattice structure,[10] first investigations should emphasize on aluminium matrix composites. In addition, aluminium alloys comprise two major advantages: the simple fabrication process of the material itself and also the popularity of aluminium lightweight constructions. No alternative construction material allows such cost-efficient extrusion of complex profile geometries as aluminium.[11]

The difference in thermal expansion coefficients of matrix and reinforcing elements may cause problems when the profile is heat-treated. As a near-net-shape process is desired, cold-hardening alloys should be preferred. Table 1 lists a number of aluminium wrought alloys with predominantly good extrudability. This property is of major importance as a low extrusion pressure is required, simultaneously decreasing the stress applied to the reinforcing element and hence substantially increasing the process stability.

Among the materials listed, only the alloys of the 6000 series show cold-hardenability increasing the strength substantially. 6060 and 6063 exhibit ultimate tensile strengths of approximately 150 MPa (temper T1 and T4); the ultimate tensile strength of 6005A is slightly higher.[11] However, EN AW-6060 shows a slightly better corrosion resistance and is the most commonly used material for automotive light-weight structures, featuring an excellent surface quality and superior load transfer properties even at reduced wall thickness.[11] Therefore, the matrix material of choice for first investigations on compound-extruded profiles for structural components is the aluminium wrought alloy EN AW-6060.

Reinforcement material. Requirements: As an important criterion in the course of the materials selection process, the ratio $\sigma_{\max}/\mathrm{E}$ is the determining material index regarding the process requirements as derived from Equation 1. Since σ_y is a upper limit for $\sigma_{\max}$, both values are supposed to be identical in the mathematical consideration. The material index to be maximised is therefore σ_y/E. Given that the precise magnitude of the stress caused by the compound extrusion process is unknown, one constraint in the selection process is a maximum ultimate strength of the reinforcing element – it supposedly is at least higher than the ultimate tensile strength of EN AW-6060 (min. 120 MPa for T4 temper), in order to achieve a reinforcing effect. The latter issue also requires a lower limit for E of 69 GPa, which is the Young's modulus of the aluminium alloy

Table 1. Aluminium wrought alloys showing prominent extrudability, [7] cold hardenability, weldability and corrosion resistance. [11]

Alloy EN AW-	cold-hardenability	weldability (MIG/WIG)	corrosion resistance
1050A		very good	very good
1085		very good	very good
1098		very good	very good
1350		very good	very good
5005A		very good	very good
3103		very good	very good
6060	X	very good	very good
6063	X	very good	very good
6005A	X	very good	Good

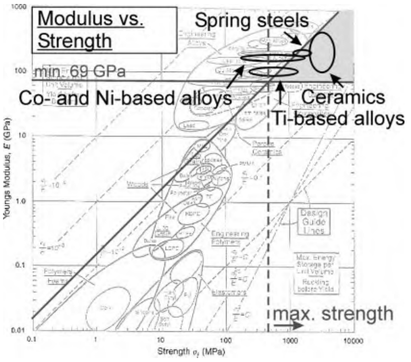

Fig. 2. Materials properties chart: Young's modulus vs. strength [12] (modified) showing the search region of potential reinforcement materials for compound-extruded lightweight profiles

6060. When identifying both constraints and the material index in the materials selection chart (see Fig. 2), the small shaded region containing titanium-, nickel- and cobalt-base alloys as well as spring steels presents qualified candidate materials. Technical ceramics may also meet the requirements as stated below.

The reinforcing elements have to resist a temperature of up to 500 °C for a short period of approximately one minute during the compound extrusion process. This temporary increase of temperature must not affect the mechanical properties adversely.

Metallic materials: Regarding the requirements, nickel- and cobalt-base alloys showing good mechanical properties both at room and extrusion temperature outperform titanium alloys and spring steels which allow much lower maximum process temperatures[13,14] eventually causing a strength loss during short-time heating.

Among the suitable metal alloys identified, titanium alloys feature the lowest Young's modulus of 100 GPa, offering no significant increase in stiffness in a titanium wire-aluminium composite.

The consequence is the preference of nickel- or cobalt-base alloys or spring steels. However, the temperature influence on the latter alternative has to be investigated, especially regarding a potential decrease of the ultimate tensile strength at high extrusion temperatures. Regarding the maximum ultimate tensile strength of the metallic reinforcing elements attainable, nickel- and cobalt-base alloys feature ultimate tensile strengths of up to 1500 to 1800 MPa (manufacturers' specification for Inconel® 718 and Haynes® 25, spring temper). Spring steel 1.4310 has a minimum ultimate tensile strength of 1950 MPa at a diameter of approximately 1 mm.[14] Additionally, with a Young's modulus of 180–225 GPa (see Fig. 2), reinforcing elements made from the metallic materials mentioned provide an increase of stiffness and strength for the overall compound. The ratio of yield and ultimate tensile strength for spring-tempered materials is close to 1, the resulting strain thus is low. In the annealed state, the cobalt-base alloy Haynes® 25 exhibits a ratio of yield and ultimate tensile strength of 0,5 and an overall lower strength level (manufacturers' specifications) featuring a deformation reserve which allows the reinforcing element to react on the load applied during the extrusion process. Everything considered, the three metallic systems offer three different mechanical characteristics:

spring tempered cobalt- and nickel-base alloys: high yield and ultimate tensile strengths and therefore elastic behaviour both at extrusion temperature and room temperature;

spring steels: high yield and ultimate tensile strengths at least at room temperature and eventually at extrusion temperature, if the thermal load is lower or only for a short time higher than the maximum service temperature;

annealed cobalt-base alloys (e.g. Haynes® 25): relatively high ultimate tensile strength in comparison to the yield strength at an overall reduced level of mechanical properties featuring the opportunity of strain hardening at extrusion temperature and simultaneously offering a deformation reserve compared to spring tempered materials.

Ceramic materials: As bulk ceramics feature insufficient ultimate tensile strengths, ceramic reinforcing elements may only be considered in the form of fibres or yarns, featuring high Young's moduli and ultimate tensile strengths at an effective reinforcing element diameter of some microns, which reduces the applied bending strength substantially. Therefore, the plotted region refers to the mechanical properties of ceramic fibres, for example alumina, boron or carbon fibres, fulfilling all given requirements. The application of commercially available carbon fibres promises maximum reinforcement since Young's moduli range between 121 and 490 GPa and the ultimate tensile strengths between 2,5 and 5,7 GPa. Additionally the density of 1,8 g/cm^3 is considerably lower than the density of aluminium.[15–17] Regarding the oxidation resistance, alumina fibres outperform carbon fibres. However, ceramic fibres in general cannot withstand shear or tensile stresses occurring during the compound extrusion process without elaborate preparation (e.g. infiltration of bundles).

Table 2 gives an overview on the mechanical properties of potential reinforcement materials.

Reinforcing element geometry and interface design: Metallic materials: Besides the material's properties, the availability of the reinforcing element of the desired shape, such as wires or fibres, is decisive for the application of a certain reinforcing material. All materials selected are readily available in such specifications. However, spring tempered wires made from titanium-, nickel- or cobalt-base alloys are rather expensive when compared to spring steel wires which have found a wide range of applications, not at least for the reason of costs. Regarding a metal matrix composite, the load transfer between fibre and matrix is of paramount importance in order to achieve improved mechanical properties when compared to non-reinforced profiles. A drawn wire exhibiting a smooth surface per se provides a friction-type connection only. Nevertheless, metal matrix composites with reinforcing steel wires have already revealed good mechanical properties.[18] Additionally,

Table 2. Potential reinforcement materials and their mechanical properties (manufacturer's specifications and Saeger [15])

Material	approx. ultimate tensile strength [MPa]	Young's modulus [GPa]	Density [g/cm^3]	Specific modulus [GPa·cm^3/g]
Stainless spring steels	1900–2500	200–210	7,8	26,3
Nickel-base alloys (spring temper)	1300–1600	205	8,1	25,3
Cobalt-base alloys (spring temper)	1400–1800	225	9,1	24,7
Cobalt-base alloys (annealed)	950–1100	225	9,1	24,7
Alumina fibres	up to 3100	up to 400	4,0	up to 100
Carbon fibres	up to 5700	up to 600	1,8	up to 333
Boron fibres	up to 2800	up to 420	2,4	up to 175

an elevated extrusion temperature may enhance chemical interdiffusion in case of mutual solubility of matrix and reinforcement components resulting in a strong metallurgical bond. Indeed, the width of the diffusion zone is below 100 nm as the process parameters – assuming a conventional extrusion temperature of approximately 500 °C for variable periods between some seconds and some minutes – only allow for short-range diffusion. Nevertheless, the evolution of intermetallic compounds containing iron and aluminium have been reported for compound-extruded aluminium-steel composites.[3]

Two interface design strategies may increase the load transfer between fibre and matrix: First, the application of a coating on the reinforcing element, which promotes chemical interdiffusion. Furthermore, a low melting coating material may act as in-situ lubricant during the compound extrusion process and may reduce the interfacial shear forces when the wire comes into contact with the flowing matrix and consequently the peril of a reinforcing element fracture. In that regard, a zinc layer may turn out to be a solution regarding the following aspects:

Zinc has a comparably low melting point of 420 °C, which is within the range of conventional extrusion temperatures and therefore allows for the formation of a friction-reducing layer.

The Al-Zn binary phase diagram reveals a maximum solubility of 83 wt% zinc in the considered temperature range.[19]

Both nickel and cobalt show a solubility for zinc both at room temperature and at extrusion temperature.[19]

Electro-galvanizing of zinc on stainless spring steels using nickel strike is an established technique and therefore a competitive process for bulk production. Additionally, thermal spraying of zinc coatings allows for bench-scale processing for first investigations

The second strategy to improve the interfacial load transfer is a form fit requiring a structured surface of the reinforcing element. Ropes and flexible shafts grant this option while single wires do not. Additionally ropes and flexible shafts provide the benefit of an internal load transfer within the reinforcing element as the single wires are twisted to ensure the transferred load on the reinforcing element distributed among the single wires. Additionally, ropes and flexible shafts share one major

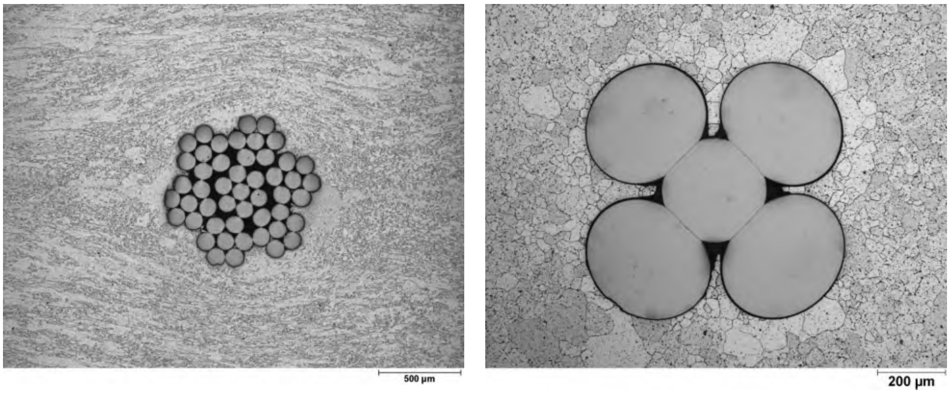

Fig. 3. Metallographic micrographs of compound-extruded aluminium matrix compounds: 7 × 7 rope made from nickel-base alloy 2.4851 (left), 1 × 5 flexible shaft made from spring steel 1.4310 (right), both providing a form fit.

advantage: As the diameter of each wire within the reinforcing element is small in comparison to the effective diameter of the complete rope or shaft, the maximum bending stress (Eq. 1) of the reinforcing element decreases substantially. Figure 3 shows metallographic micrographs of compound-extruded aluminium matrix profiles reinforced with ropes and flexible shafts, either of which providing a form fit as the aluminium matrix fills the spaces between the wires on the outside.

Despite the likewise given option of a form fit, flexible shafts and ropes reveal different mechanical properties arising from tensile tests on different types of ropes and flexible shafts. The results are displayed in Figure 4. The effective diameter of the specimens was 1 mm with each cord wire having a diameter of 100 μm up to 300 μm. The wires were spring tempered with each having minimum tensile strengths of 1800–1960 MPa (manufacturers' specifications). Though mechanical properties of the materials used are comparable, the differences due to the specimens' design are evident: the flexible shaft in 1 × 5 construction (Fig. 3) reveals a total elongation to fracture of approximately 22 % in contrast to ropes with total elongation to fracture of roughly 4 %. Furthermore, the ultimate tensile strength of the tested flexible shaft is significantly lower. The difference in ultimate tensile strength for the tested ropes is due to both different designs (1 × 7 and 7 × 7) with a varying number of single wires and therefore contents of reinforcing fibres and a difference of ultimate tensile strengths for the wire materials used.

Accordingly, ropes provide an improved reinforcing effect regarding the ultimate tensile strength compared to flexible shafts at identical element diameter whereas flexible shafts feature high total strains, which may retard the fracture of the reinforcing element incorporated in the profile when an external load is applied to it.

Ceramic reinforcements: Within an unspun bundle of ceramic fibres, the shear stress, which is applied on the circumference of the reinforcing element during the embedding process exclusively, loads the single fibres located at the outside. The lack of internal load transfer within the bundle causes an exceeding of the tensile strength of the fibres at the peripheral surface and the fracture of those fibres. Accordingly, this process proceeds until all single fibres remain fractured. Therefore, ceramic fibres have to be prepared for the application in compound extrusion by spinning a yarn (improve of internal load transfer) or being coated (interfacial design). The potential to improve the load transfer across the reinforcing element/matrix interface by a metallurgical bond has already been discussed. It has been shown that the mechanism using a chemical bond can be combined with a form fit of the reinforcing element. Such combination is well known for carbon/aluminium MMCs, which is a high-performance product excelling due to the carbon fibre's high specific strength and stiffness. The use of bundles composed of single carbon fibres has caused difficulties during the embedding process as mentioned above. In addition, the poor wetting behaviour between graphite and molten aluminium[17] does not promote interfacial shear strength. High extrusion temperatures above 500 °C may enhance the formation of brittle aluminium carbide (Al_4C_3), which may cause the deterioration of the composite.[20] In the absence of an effective coating aluminium carbide can form at a relatively high rate, either by platelet formation or by growth of a continuous layer resulting in fibre pitting and a gradual reduction in fibre cross section[20] Therefore, a modification of the carbon fibre surface is necessary both to increase the wetting properties and to prevent carbide formation. In recent studies, the deposition of copper and nickel on graphite fibres has been successfully performed.[21,22] As described above, in electro-galvanizing of zinc on stainless steels also a nickel intermediate layer is deposited, in order to promote the adhesion of zinc. Consequently, nickel coated graphite fibres are considered to be a candidate solution for compound-extruded compounds featuring a multilayer interface: The nickel coating on the graphite fibre has been shown to prevent the formation of aluminium carbide. The electro-deposited zinc layer may not only promote the chemical interdiffusion but also serve as an in-situ lubricant during the compound extrusion process. Insofar, the interface of the outermost coating layer and the matrix material would be identical for both stainless steels and graphite fibres. Fibre-reinforced metal matrix compound wires represent a further auspicious configuration for non-metallic reinforcements.[23] At these, the reinforcing ceramic fibres are embedded in the desired light-metal matrix using a continuous pressure infiltration process resulting in a composite wire. Such wire could serve as reinforcing element for compound-extruded profiles providing an internal load transfer and hence overcoming the embedding difficulties of fibre bundles. Additionally, using the same matrix material for the composite wire and the compound-extruded profile should prevent interfacial problems.

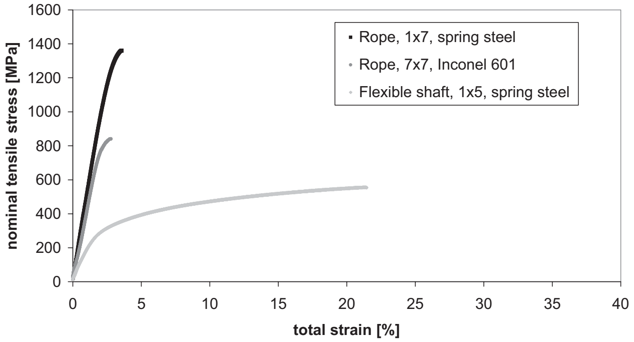

Fig. 4. Nominal tensile stress-total strain diagram for tensile tests on flexible shafts and ropes.

Summary and conclusions: In this contribution, we have provided a basic discussion of selection criteria of materials for the design of compound-extruded aluminium matrix compounds for structural components. In addition to the most promising combination of aluminium and steel,[2,3] further possible materials combinations for compound-extruded aluminium profiles have been discussed, featuring each different mechanical characteristics. In this context, alternative metal reinforcement materials were named to be spring tempered nickel- and cobalt-base alloys which both withstand high tensile stresses at the extrusion temperature. Additionally, annealed cobalt-base alloys feature the opportunity of strain hardening at the extrusion temperature and simultaneously offer a deformation buffer as compared to spring-tempered materials. Nevertheless, the combination of aluminium and steel will be the most cost effective and functional solution.

All the presented metal reinforcing elements, which fulfil the requirements of the compound extrusion process, may feature interdiffusion at the reinforcing element/matrix interface. Coating the reinforcing element with zinc may enhance this effect. An adequate coating is of prime importance when carbon/aluminium composites are to be accomplished which are usually prone to the formation of brittle intermetallic phases. In this regard, the use of composite wires may overcome interfacial problems in compound-extruded profiles.

Eventually, the geometry of the reinforcing element has a considerable influence on the load transfer between the matrix and the reinforcing elements since ropes, flexible shafts or spun yarns may provide a form fit, while smooth wires do not. The smaller diameter of the single fibres or cords allows for smaller feeding radii.

The concepts presented are a starting point for the investigations on compound-extruded lightweight profiles for structural components considering the systematic review of potential matrix and reinforcement materials as well as the reinforcement and interfacial design. First metallographic investigations on rope-reinforced profiles produced by compound extrusion look auspicious. However, the broad characterization of the mechanical and interfacial properties of the compounds is compulsory and intended.

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