Abstract

Profiles of various shapes and cross-sections are a central element of today's chassis, drive trains and car-bodies, especially for constructions based on a space-frame concept. From a profile manufacturer's point of view, suitable classification criteria for the profiles needed are the kind of curvature, the kind of cross-section and the design of the connection area. All these features might need different manufacturing processes like rolling, extruding, forging, bending etc. Until recently the pultrusion as the only real mass production process for fiber reinforced profiles could only be used to manufacture straight profiles. This was a kind of show-stopper for the application of fiber reinforcement in mass produced vehicles. With the newly developed "Radius-Pultrusion" process, applying a moving and elastic mold to create the profiles this barrier has been overcome. The mass production of profiles with constant curves of practically any radius is already state of the art. The manufacturing of profiles with variable radii has been demonstrated and even the production of variable cross-sections is a potential of this technology. Theory, practical examples and also some examples for the equipment are described in the following.

Fiber Reinforced Profiles for Car Bodies and Chassis

The design of profiles in automotive industry ranges from highly complex profiles like the ones used for the A- and B-column of space-frame bodies to profiles with constant curvature around moving window components and simple straight profiles with various cross-sections used in typical parts in the chassis-area. Guide rails, stabilizers and also coil springs are typical examples of such profiles. The theoretical benefits of using fiber reinforced material instead of steel and aluminum have been widely described in many publications. The ability of fiber reinforced profiles to meet the requirements of the automotive industry with respect to long term fatigue resistance and also crash behavior has been proven by applications like the body of the i3 of BMW (2013), the leaf springs in the Corvette (since 1981) [9] and the coil spring for the Audi A6 (2014) [10].

Depending on the application, the profile's low weight, potentially higher strength and stiffness or their corrosion resistance are the main advantages. Nevertheless, the production volume of fiber reinforced profiles has remained at a level of approx. 0,01 % of the overall profile production [2, 3].

A comparison of the design features of steel, aluminum and pultruded fiber reinforced profiles (see table 1) clearly identifies one of the major reasons for this situation: The limitation of pultrusion, the only mass production process for fiber reinforced profiles, to straight profiles.
From the very beginning of the development of pultrusion, considerable effort has been made to overcome this limitation. One of the most well-known but not very successful efforts was made by B. Goldsworthy, one of the inventors of the pultrusion process [1]. In his process he used a longitudinally divided mold with one half mounted on a rotating "puller".

In 2008/9 we developed a process with a nearly unlimited applicability for the manufacturing of curved profiles with a constant radius and curves which can be described as an addition of curves with constant radii. This "Radius-Pultrusion-Process" has become the brand name for all such processes [4][5]. After various development and production experiences with constant curves we moved on to the technology of manufacturing variable curves. The feasibility of this process was demonstrated in 2015.

The basic theory of "Radius-Pultrusion", its extension to profiles with variable radii and the kind of parts and machinery realized so far, will be described in the following sections.

Table 1. Comparison of the design features of different profile materials and production methods of fiber reinforced materials:
++ = industrial standard; +- = slightly difficult; -- = impossible

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<tr>
<th>Design features of different profile materials and production methods</th>
<th>Steel</th>
<th>Aluminum</th>
<th>FRP-Pultrusion</th>
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1. The Reversed Pultrusion Process - The "Radius-Pultrusion"

1.1. Reverting the pultrusion process as the key to curved profiles

The simple reason why the standard pultrusion process is limited to straight profiles lies in the impossibility to pull a profile through a curved mold. Whereas a curved mold can be moved over a curved profile like a rotating nut moves over a screw.
The different mechanics of both processes are illustrated in Fig. 1 and 2. In standard pultrusion the pulling force at the end of the profile leads to a force rectangular to the profile axis. This force directly increases the friction along the profile and blocks the movement. The smaller the radius in a given length of mold, the bigger this rectangular force is. As in pultrusion, the adhesion of the profile to the wall is already high, since the profile is moved during the polymerization of the resin, this effect makes the pultrusion even of big radii impossible.

Fig. 1. Resulting forces when pulling force is applied to a profile in a curved mould; Black: Pulling force \((F_p)\); Green: Force parallel to the interface of profile and mold \((F_t)\); Brown: Force rectangular to the interface \((F_r)\)

Fig. 2. Resulting forces if a mould with constant curvature is rotated over a profile; Red: Movement of the mould; Black: Forces tangential to the interface between profile and mould
If alternatively the profile is fixed and the mold is the moving part, the forces generated by the movement are orientated parallel to the profile axis and thus no rising friction is generated along the profile (Fig. 2). So no blocking force is generated in the mold along the axis of the profile. Since fixating the profile is naturally done by holding the profile at the end of the mold, also moving the mold creates a force rectangular to the axis of the profile, in this case at the end of the mold. This force will be the higher, the longer an unsupported distance between the mold and the fixation point of the profile is in relation to the radius.

Due to this effect, the mold has to move back and forth in small steps to limit this blocking force at the end of the mold. These steps have to be smaller, the tinier the radius is. On the whole, the profile is no longer pulled through the mold but in reversion of the standard pultrusion the mold moves in small steps over the profile and can thus create both curved profiles and straight profiles without barely any limitation regarding radius and - in case of helical profiles - pitch. The difference between the features of metallic and FRP-profiles decreases as shown in the fifth column in table 1.

Examples of profiles created by this type of moving mould process, some of them either approved or targeted at the automotive market, are shown in Fig. 3

1.2. Elastic molds for variable radii

As long as the molds are stiff, the reverted process described above can only be used to manufacture curved profiles with a constant cross-section where the curvature can be described as a sum of constant radii. If the mold is elastic, it is quite easy to also imagine the production of profiles with variable curvature like e.g. stabilizers, roof reinforcement or some bumpers. Even a variable cross-section like parts for the A- or B-column are possible based on the same process principle [5, 6].
To create and control an elastic mold for a pultrusion or moving-mold process a number of boundary conditions have to be taken into consideration.

Typical resins for the pultrusion process have a particularly low viscosity in the first stages of the process. Any transversal gap or slit in the mold can cause problems as the resin will fill such structures, cure and block the movement of the profile.

The composite material undergoes changes in volume during the process. The combination of thermal expansion and chemical shrinking leads to a higher volume in the gel-zone and a smaller volume at the end of the consolidation. In a stiff mold, this leads to high pressure in the gel-zone. In an elastic mold, this can deform the mold and lead to a blocking of the process.

The final shape and the fiber distribution in the profile are fixated in the gel-zone. If the cross-section of an elastic mold is distorted by the bending process, this shape might not fit the following part and can cause a blocking of the process as well.

As a consequence of these boundary conditions, an elastic mold for manufacturing profiles with variable radii cannot be made of a single material in most cases. The requirement to keep a constant cross-section during the bending process does not allow to simply use an elastic material for the mold. Due to geometrical reasons, the cross-section of a cavity in any mold made from a continuous elastic material will change its shape as soon as the mold is bent. On the other hand, a continuous wall-material for the cavity is required because no transversal gaps or slits are allowed.

Thus, any mold for this manufacturing process has to have at least two components: One component which stabilizes the cross-section when bended (e.g. like the pressure members of the elastic steel-tubing used in the oil industry) and a second component which creates the closed surface of the cavity.

The stabilizing component can be realized either by coupled segments or a coil with the required cross-section. Two examples of such stabilizing components created by a 3-D-printing process are shown in Fig. 4.

For the inner liner there are three very different approaches:
The first approach is to use a kind of tube made from silicone, PTFE or similar material as inner liner which is supported by the stabilizing component.

The second approach is to encase the profile before entering the mold with a flexible cover which is transported through the process together with the profile. Instead of an inner liner, now this encasement prevents the resin from pouring into the slits of the stabilizing component at the beginning of the curing process.

The third approach is to use a thixotropic resin which reacts very fast especially at the surface in order to create a revolving encasement. This encasement prevents the pouring and will be a part of the final profile. Depending on the resins, different types may be used for the outmost layer of the profile and for the inner part of the cross-section (Fig. 5).
Fig. 4. Two design examples of stabilizing components for elastic molds created by 3-D-printing (sintering). For real molding applications metallic 3-D-sintering must be used; Top: Waved spiral design: high flexibility, circular liner support; Bottom: Toothed spiral design: good flexibility, overlapping liner support.

This third approach can be regarded as the most elegant and promising for the future. There would only be a small risk for the profile to stick in the mold and even lubrication is possible because the outside of the profile is already consolidated. As no inner liner is required, design and manufacturing of the mold itself could be reduced to the creation of the stabilizing component only (e.g. by 3-D-Printing as in Fig. 4). For this approach resin systems with the ability of “snap-curing” - at least for thin layers - are needed. As the process is entirely new, no applicable materials are on the market. Therefore, we had to use the first approach for the tool design and we combined a stabilizing component with an inner liner for the proof of concept runs.

Irrespective of the kind of mold design, the task to create an elastic mold and the process itself will be easier, the shorter the mold can be made. All critical points like deformation of the cross-section, high pulling forces due to the adhesion of the resin and the control of the mold itself will be easier with a short mold. In the ideal form of the process, the mold is reduced to an aperture which moves in very short steps back and forth along the curve of the required profile while the resin is curing instantly when entering the aperture. In this ideal form, the resemblance of the moving mold process (stepwise operation) to the typical 3-D-Printing processes (layerwise operation) becomes quite obvious.
Fig. 5. Two approaches for the design of an elastic mould; Top: Segmented stabilizing component (light blue) with inner liner (dark blue); Bottom: Segmented stabilizing component (light blue) with fast curing resin building an encasement within the first segment. (Yellow/Orange: Gel-zone)

Like the 3-D-Printing process the moving-mold-process has the potential to be a disruptive technology for the world of profiles. As shown in table 2. the features and design possibilities of fiber reinforced profiles created in moving-mold-processes are similar to or even better than the features of steel and aluminum profiles.

Fig. 6: Setup for first tests of the elastic mold concept:
1: Gripper; 2: Segmented mold; 3: Steering link; 4: Profile leaving the mold
1.3. First Operation of an elastic mold

For a first demonstration of the capabilities of the Radius-Pultrusion with an elastic mold we chose a steel braid reinforced PTFE-tube as inner liner which was guided by separate, individually heated guiding segments.

These guiding segments were mounted on the segments of a steering chain which itself is guided in the slot of a steering link as shown in Fig. 6 and 7. The steering link itself consists of a chain of longer segments, with the required curvature along their axis. In each process step the mold moves along the link and then the link and mold move back together. Thus, the chain of the steering link segments moves through the machine step by step while the chain of guiding segments moves only back and forth. When a segment of the steering link leaves the process together with the profile it gets disconnected and moved back to the start of the process, where it is reconnected to the steering link chain.

With this setup, we managed to establish a continuous process which is able to run for at least 2 hours and manufacture a round profile of a diameter of 12 mm with a variable curvature. The process speed was between 10 and 15 cm/min which was quite slow due to the inefficient heat transfer caused by the segmentation itself, together with the low heat transfer coefficient of the PTFE material of the inner liner.

![Fig. 7: Two different profiles manufactured with a segmented mold. Left: Continuous sinusoidal curved profile; Right: Profile with sinusoidal (1) and straight segments (2) combined](image)
As to be expected in a first run, the process stability was limited. After 2-3 hours, severe residues had built up in the mold leading to a blocking of the process. The thermal dimensional growth of the resin in the gel-zone above mentioned had pressed the PTFE material into the steel braid and caused a rippled structure on the surface of the inner liner. In these ripples the residues had built up. Nevertheless, using this setup we were not only able to demonstrate the manufacturing of a sinusoidal shaped curve as shown in Fig. 5 but also the combination of sinusoidal shaped and straight segments in one profile (Fig. 7). To manufacture this combination we replaced one of the segments of the steering link with a straight groove instead of a sinusoidal shaped groove as in the other segments.

Fig. 8. Moving-mold process controlled by a steering link.
Step 1: Gripper (1) closed, steering link (3) connected to the machine base; Step 2: Mold (2) moves backwards, curvature controlled by groove in steering link; Step 3: Gripper opens, mold moves forward together with consolidated profile (4) and steering link now connected to mold.
2. Machinery for the Radius-Pultrusion Process

As shown in fig. 9 we used the puller unit of a modified standard pultrusion line for the first test of the process with the elastic mold, controlled by a moving guide rail. In the same way such modified lines can be used for most curved profiles with radii down to 1800 mm (70°). For constant curvatures, a fixed guide rail is mounted on the machine bed and a stiff mold is moved back and forth along this guide rail by one of the pullers.

As long as the curvature is in the range mentioned above, it doesn’t matter whether the curve is 2- or 3-dimensional in space. Two examples of setups for two dimensional curves, one for horizontal and one for vertical curvatures, are shown in fig. 10. A combination of both can be used to create nearly any curve that can be seen as a superposition of constant radii, as described in sec. 1.2. Whether the major curvature of the guide rail is orientated parallel to the horizontal or the vertical axis, depends on the orientation of the profile cross-section with respect to the radius. If the long axis of a profile cross-section is parallel to the axis of curvature, the axis of the guide rail curvature should be orientated horizontally. This would be the best solution for impregnation as well as fiber orientation. If the short axis of a profile is parallel to the axis of curvature, the axis of the guide rail should be orientated in the vertical direction accordingly.

For radii smaller than 1800 mm, it is no longer possible to use a modified straight machine. For radii between 40 mm and 1800 mm, rotating machines with a horizontal or vertical central axis have to be used. The orientation of the axis depends on the size and the application of the profile. An example of such a machine, especially designed for the manufacturing of coils, is shown in fig. 11. For the orientation of the axis, similar rules apply as for the guide rails on the linear machine base.
Fig. 10: Two examples for the setup of lines suited for radii down to 1800 mm - 1: Mold on Mold table 2: gripper/gripper table 3: Guide rails for curvature control 4: Machine bed

Fig. 11: Design and operating machine for small radii between 40 and 300 mm, suited for curved and coil-like profiles. Mold and Gripper shown are for a radius of 120 mm
Table 2. Comparison of the design features of different profile materials and the production methods for fiber reinforced profiles including the prospects of the Radius-Pultrusion process:
++ = industrial standard; +- = slightly difficult; -- = impossible

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3. Summary and Further Developments

The Radius-Pultrusion process is a new kind of mass production process for fiber reinforced profiles, based on the idea of a moving mold. It has the potential to realize mass production of nearly all kinds of profiles used in car-bodies and also the chassis area. At the present stage of development, the manufacturing of all profiles which can be defined as a superposition of constant radii is possible and has already been realized and proven for some components.

The results of test runs and experiments with an elastic mold (see sec. 1.2 and 1.3.) are proof of concept of the Radius-Pultrusion process for variable curvature. With this modification, profiles with nearly any kind of constant cross-section and curvature are also possible. With further modifications, like molds with continuous variable cross-section, this process has the potential to even outperform most kinds of profile technologies for conventional materials (see table 2).

The presently available machinery for the Radius-Pultrusion process allows the manufacturing of curved profiles with radii down to 40 mm (1.8”) and any order of pitch. The machinery is also ready for variable pitch and radii, depending on the further development of mold and process technology. Further developments of the machinery are targeting especially the production of entire frames which can be used for complete B- and C-segment or backrests of seats, not to mention other applications in industry [11].
Acknowledgements

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Bibliography


3. Elliot, M; Agrawal, A; et al.; Ernest & Young Publication; Brochure "Global-Steel-2014";


5. Jansen, K; Weidler, D; Hoffmann, M; Method and device for the production of a plastic profile; EP-Patent, WO 2008/116560, 2008.02.01


7. BASF AG; "High lights" - Website; http://www.standort-ludwigshafen.basf.de/group/corporate/site-ludwigshafen/es/literature-document/Brand+Darocur-Brochure--High+lights+Radiation+curing+with+resins+and+photoinitiators+for+industrial+coatings+and+graphic+arts+Laromer+Irgacur+Lucirin+Darocur-English.pdf; Access Date: 2016.01.10

8. Deuteron GmbH; Brochure "Photoinitiators"; Website;
   http://deuteron.com/cosmoshop/default/pix/pdf/lit/D/flyer-uv-initiators-E.pdf; Access Date: 2016.01.10

9. Power Automedia; http://www.corvetteonline.com/history-2/the-top-5-technological-advancements-in-corvette-history/ Access Date: 2016.06.05

10. Verlag Moderne Industrie; http://www.automobil-produktion.de/technik-produktion/fahrzeugtechnik/audi-setzt-federn-aus-gfk-ein-343.html/ Access Date: 2016.06.05

11. Jansen, K.; Machines for Radius, Curves and Frames, World Pultrusion Conference, Prague June, 8-10, 2016;