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Remote Laser Cutting of CFRP: Improvements in the Cut Surface

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Abstract

In the automotive industry carbon fibre reinforced plastics (CFRP) are considered as a future key material to reduce the weight of the vehicle. Therefore, capable production techniques are required to process this material in mass industry. E.g., state of the art methods for cutting are limited by the high tool wear or the feasible feed rate. Laser cutting processes are still under investigation. This paper presents detailed new studies on remote laser cutting of CFRP focusing on the influence of the material properties and the quality of the cut surface. By adding light absorbing soot particles to the resin of the matrix, the cutting process is improved and fewer defects emerge.

Keywords: CFRP; Laser Cutting; Single Mode; Machining

1. Motivation

The overall goals of the politics of transportation in Europe are strongly affected by the climate change, the shortage of global energy resources and the increasing energy costs. One approach in this matter is electric mobility combined with innovative lightweight construction concepts. In addition to an electric power train the operative costs of automobiles can only be reduced significantly by the strict application of lightweight constructions to minimize the vehicle weight. In the automotive industry carbon fibre reinforced plastics (CFRP) are considered as a future key material to meet lightweight construction needs. In comparison to conventional materials, like aluminium alloys or steel, CFRP has a high specific strength, high stiffness and excellent corrosion resistance. While CFRP is already quite common in high end sports equipment and aerospace industry, technologies which are suitable for mass

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production are still required. Economic technologies for joining and cutting as well the recycling issues are still under investigations.

2. State of the Art

The state of the art methods are strongly limited by their economic feasibility. Two methods are quite common for CFRP cutting: milling and water jet cutting. Milling is a capable process but the cut surface quality is strongly affected by the high tool wear which occurs during the milling process [1]. On the one hand, water jet cutting is an innovative technique for cutting of several materials [2]. Studies on the delamination in an abrasive water jet process [3] and a comparison between water jet and laser cutting demonstrated the suitability of this technique [4]. But on the other hand the small feed rate compared to a laser process strongly limits the economic feasibility.

While laser cutting of metals can already provide a good edge quality, the results are not yet satisfying when processing CFRP and further investigations are in progress. As the laser power and the brilliance of new laser systems increase, nowadays laser cutting becomes more and more attractive for industrial applications. Due to the high beam quality and power density, which are necessary for the evaporation of the carbon fibres, especially fibre lasers appear to be suitable to cut CFRP. The influencing factors on the kerf's geometry and on the heat affected zone (HAZ) are determined within investigations on the process parameters working with an Nd:YAG laser [5]. Beyond that, further investigations provide the correlation between cutting parameters and the static strength of laser cut CFRP [6]. As laser cutting involves a heat affected zone by the thermal evaporation, a method to seal the exposed fibre endings during the cutting process was developed [7]. Detailed studies on cutting CFRP with fixed optics were made by [8]. The research on remote cutting of CFRP [9] deserves particular attention. The required cutting energy is applied in several passes. As a result the thermal damage of the cut edge is reduced. This is only possible since highly brilliant laser beam sources are available [10]. Further work on analysis of thermal damage and how to minimize that was done by [11], [12].

3. Approach and Objectives

Based on those results this paper presents investigations on laser remote cutting of CFRP. In order to ablate carbon fibres efficiently a highly focussed single mode fibre laser was chosen for the experiments. The question in a first row of experiments is which surface quality is obtainable cutting conventional CFRP with a fibre volume content of approximately 45 %.This material is e.g. used for structural parts of electrified automobiles. In order to analyse the quality of edges, cross-sections were made and interpreted under a light microscope. The purpose of these investigations is to provide a deeper understanding of the relevant failure phenomena.

The second question is: Which effect has the modification of the absorption behaviour of the matrix on the surface quality? Therefore carbon black was added to the Matrix of the CFRP. Finally the number of failure phenomena is compared between the different materials.

4. Results

4.1. Process parameters

All the experiments were performed with the parameters shown in Table 1. The number of passes was varied according to the required cutting depth. For a nearly complete section of the 2.2 mm thick material a minimum number of passes of at least 25 was necessary.

Table 1. Process parameters

Parameter	Value	Unit
Wavelength λ	1068	nm
Focal diameter d_f	60	µm
Laser power output P_L	3	kW
Track speed	6000	mm/s
Number of passes	1 – 40	-
Time of waiting after each pass	600	ms

The functional principle of cutting CFRP is the ablation of material to be removed in the kerf. Thereby both the carbon fibre and the duroplastic resin have to be detached. While the resin is vaporized at approximately 500 °C the fibres need more than 3000 °C to vaporize. At the same time both constituents have completely different absorption behaviour. The carbon fibres appear highly absorbent while the resin is nearly transparent in the visible near-infrared range of light. The wavelength of the used single mode fibre laser is at 1068 nm and thus exactly in that window of low absorption. This has certain consequences when cutting conventional CFRP.

4.2. Conventional CFRP

First attempts provided a rather good kerf surface when the local fibre volume content in the cutting zone was high (Fig. 1, the laser entrance is marked by a flash):

Anyway both the beam entrance and the beam exit area show a delamination of the outside resin layer. This effect of superficial delamination can advance to both sides up to 1 mm width from the cutting line. If the cut passes zones of low fibre collocation, the conventional CFRP tends to strong fissuring in these areas (Fig. 2).

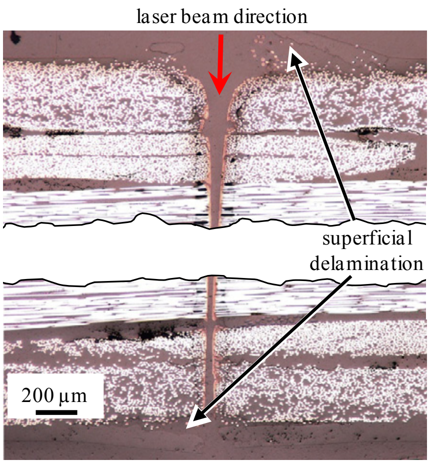

Fig. 1. Kerf surface in a zone of high fibre collocation

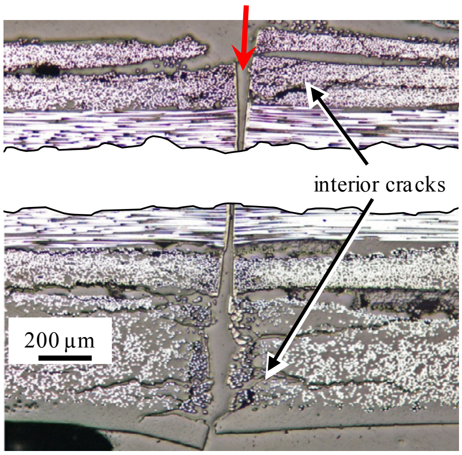

Fig. 2. Fissuring induced by laser cutting

Many cracks grow from the layer of the resin that is localized between two fibre fabric layers. These cracks may reduce drastically the fatigue strength and cannot be accepted in structural parts. The failure mechanism can be described in this case with the following detail of a cross-section (Fig. 3).

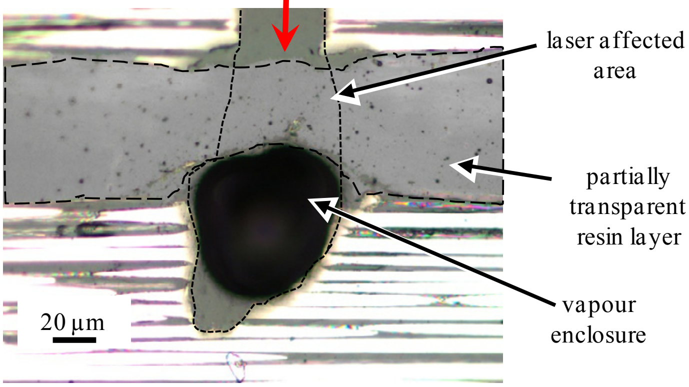

Fig. 3. Resin layer between two fibre fabrics: The vapour enclosure is a major reason for the occurrence of cracks

Although the resin layer between the upper and lower fibre fabric is still intact, there is already further ablation of carbon fibres in the section below. This is possible, because the resin is nearly transparent for the laser and the radiation of that specific wavelength just passes in order to be absorbed by the following carbon fibres. This means that the gas resulting from the ablation process is enclosed under a high pressure due to the volumetric expansion during the vaporisation of a solid material. The stress for the CFRP is in a range so that delamination or cracks are often the consequence. Such fissures usually are directed into the basic material or towards the surface. The different cases of possible fissures are shown in Fig. 4.

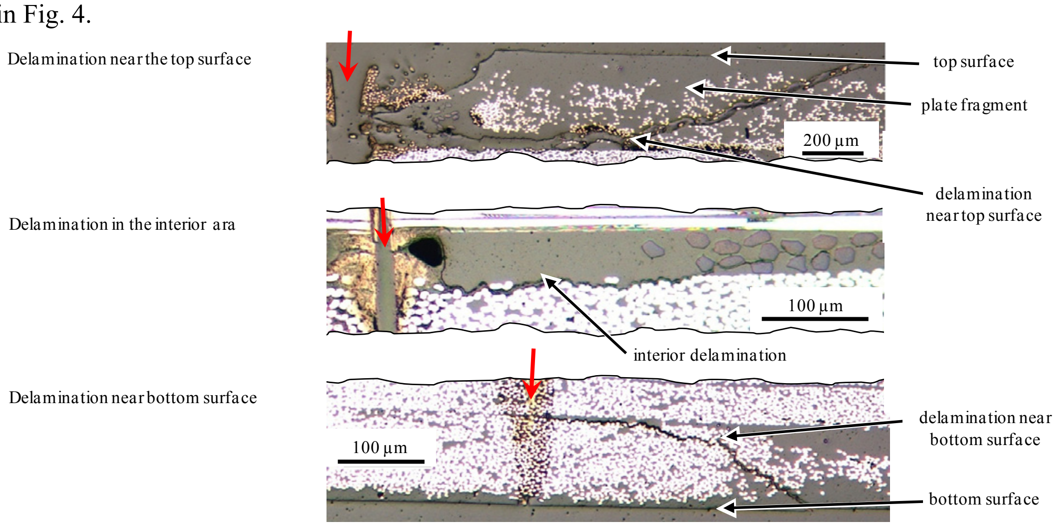

Fig. 4. Different cases of possible fissures at different locations in the plate

These could be observed up to a maximum length of 2 mm. The ones arranged in the inner section of the plate should be rated rather critically because it can be expected that such damage will grow significantly under dynamic stress.

Besides that phenomenon resin links can be observed in the kerf as well (Fig. 5). This doesn´t automatically occur along with fissures. But anyway remaining resin links hinder the separation of the cut-outs and this requires applying forces for this process.

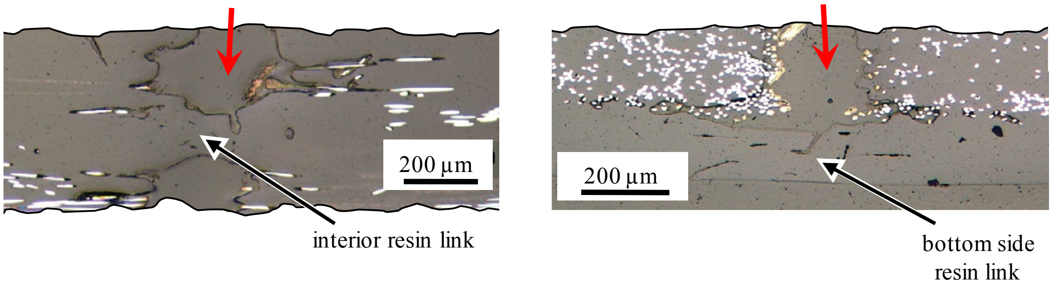

Fig. 5. Resin links at the interior area or at the bottom of the plate

Another failure phenomenon is the incomplete cut of bundles of fibres as a consequence of reflection of the laser beam in the kerf. The incomplete cut occurs especially along zones of big amounts of resin (Fig. 6).

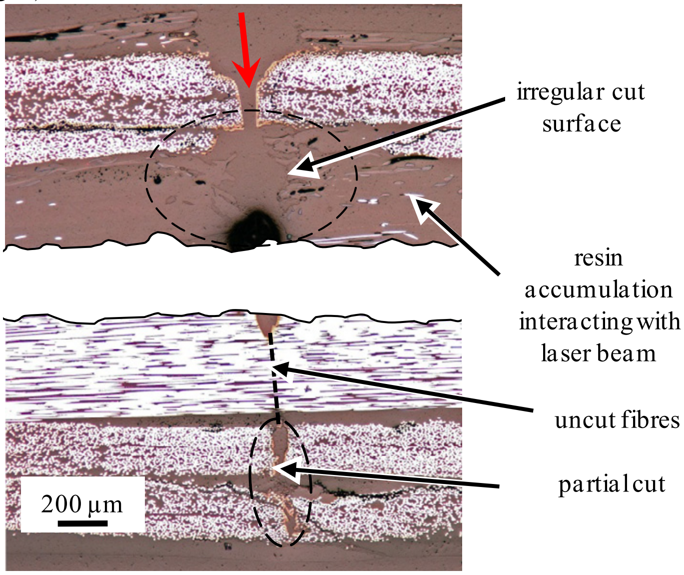

Fig. 6. Incomplete cut due to interaction of the laser beam with a resin buildup

Even if the cut passes almost the whole depth of the CFRP, a bundle of fibres in the middle is left uncut.

These uncut bundles of fibres are hindering strongly the separation of the work piece from the remainder cuts.

In areas of extremely low concentration of fibres cutting results free of defects are not possible when the described beam source is used. Either cutting is impossible due to diffuse reflection and fraction of the laser beam or different failure mechanisms at the same time make the results not acceptable. These cut results will be called outliers due to that high deviation in regions of low fibre concentration.

Cutting CFRP with a Laser imperatively causes a heat affected zone (HAZ). The width of this area varies especially depending on the time lag between the several passes of the laser. Low values for the time lag provide the result shown in Fig. 8.

In that case the width of the HAZ is up to 1 mm. In that dark appearing area both the resin and the fibres are damaged thermally. In consequence this area is considered as structurally not resilient. So a major quality criterion must be a maximum width of the HAZ at a tolerated level. The influence of this time lag on the width of a single cut is shown in Fig. 7.

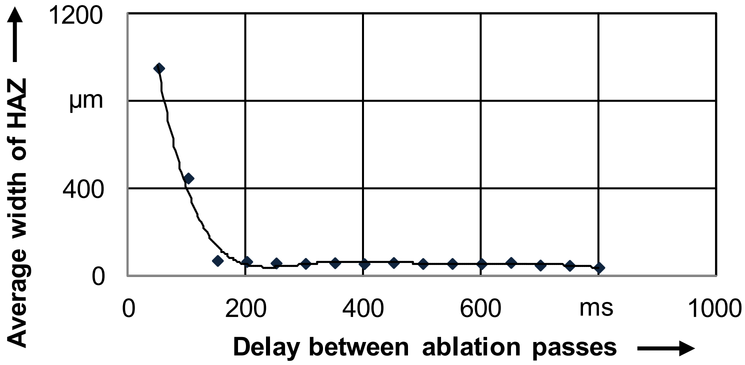

Fig. 7. Width of the HAZ in dependence of delay between passes

The width of the HAZ decreases significantly up to a time lag of 150 ms. Higher time lags do not show further effect on the width of the HAZ. Hence a cutting process with several ablation passes should be carried out with a time lag that is bigger than the described threshold value. Obviously this value has to be determined to the arrangement of the whole cutting outline accordingly: A small distance or angle between two cutting lines requires a greater time lag. If the time lag is chosen correctly, a quite narrow HAZ is possible according to Fig. 9.

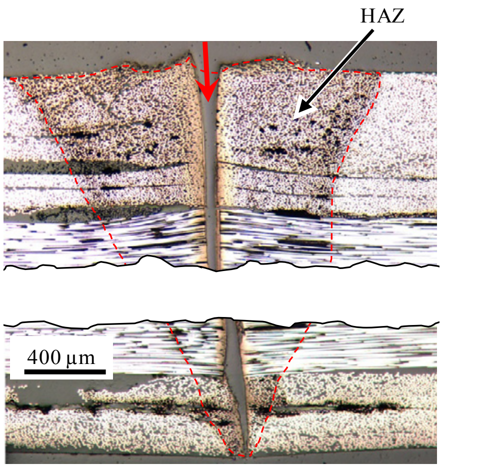

Fig. 8. Wide HAZ after cut without time lag between passes

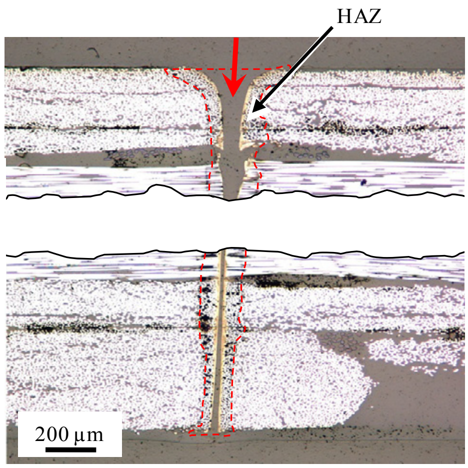

Fig. 9. Narrow HAZ after cut with time lag between passes

4.3. Model assumptions

For an industrial use of laser machining of CFRP the cut quality has to be improved. As shown in the previous section, the width of the HAZ can be reduced by conducting a time lag between the several passes. But the resin is not absorbing the used laser radiation well enough. This causes many defects as a consequence of transmission and reflection of the laser.

There are several possibilities available: One approach is using another laser whose wavelength can be absorbed by the resin. In this case a CO_2-laser could be a solution due to its emitted wavelength of 10.6 µm. In the range of far infrared the resin can absorb radiation and a direct ablation of the resin is possible.

Within this work another approach is chosen: The absorption of the resin in the CFRP is enhanced by adding light absorbing particles. In this case fine soot is distributed uniformly in the resin. This can be achieved by using pre-impregnated material. The soot can already be found in visible CFRP. It was originally added to provide a classy look. But anyway, there is no loss of strength known that might speak against admixing soot into structural parts.

4.4. Cutting of enhanced CFRP

The blackened CFRP appears more suitable for laser machining from the very beginning. In this case incomplete cuts are no longer a problem. Hence the cut part and the cut-offs can be separated easily. Furthermore, the appearance of cracks is significantly reduced (Fig. 10).

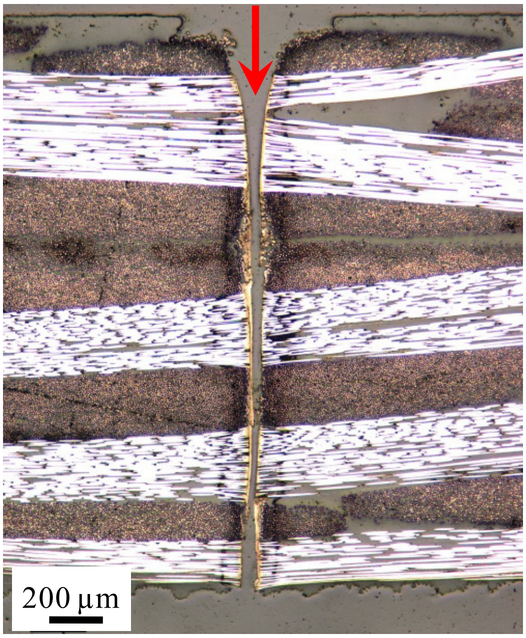

Fig. 10. Typical cut in enhanced CFRP

In this case the beam entrance and beam exit show less ablation of the outside resin layer. In contrast to the transparent resin, here the resin can be ablated directly. This can be observed in a cross section that is not carried out completely (Fig. 11).

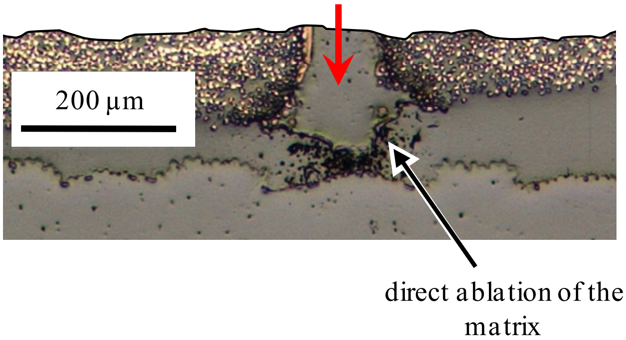

Fig. 11. Partially ablated resin layer at the bottom of the plate

The porosity of the resin layer is an effect of the absorption of the laser radiation in the resin layer. Another pass with the laser would cut such a surface completely. Also the inner area of the cut surface is significantly improved by adding soot to the matrix resin. An example of a typical transition to another fibre layer is afflicted with considerably fewer defects than before (Fig. 12).

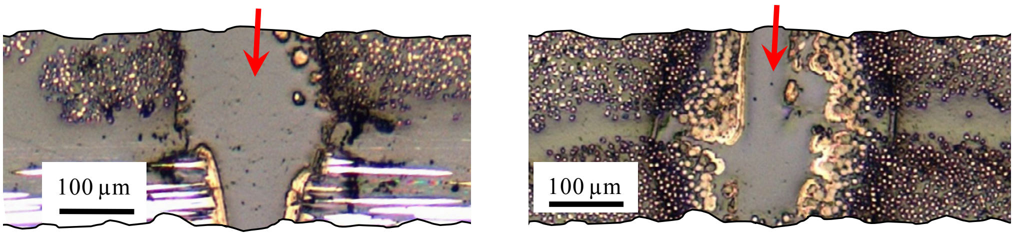

Fig. 12. Examples for cut resin layers without major defects

The method of design of experiments (DOE) was used to quantify the incidence of cutting defects in the different CFRP materials. As shown in Table 2, the proportion of fissures was reduced significantly by adding soot to the matrix resin. Also the proportion of resin links could be minimized and the number of outliers was reduced to zero.

Table 2. Analysis of the failure frequency for the different types of CFRP

Category	CFRP with transparent matrix	CFRP with blackened matrix
Total number of evaluated cross sections	206	86
Count with min. one micro fissures	171 (83 %)	19 (23 %)
Count with resin link	47 (23 %)	7 (8 %)
Count of outliers	26 (13 %)	0

It must be mentioned that the enhanced CFRP had a fibre volume content of 53 %. That might have also improved the cutting performance, but still does not explain why the edge quality has improved that drastically.

5. Conclusions

Adding absorbing particles to the resin can improve the cut quality drastically. For the first time complicated line geometries can be cut and separated easily. The work piece shows both under macroscopic (Fig. 13) and microscopic (Fig. 10, Fig. 11, Fig. 12) observation fewer defects.

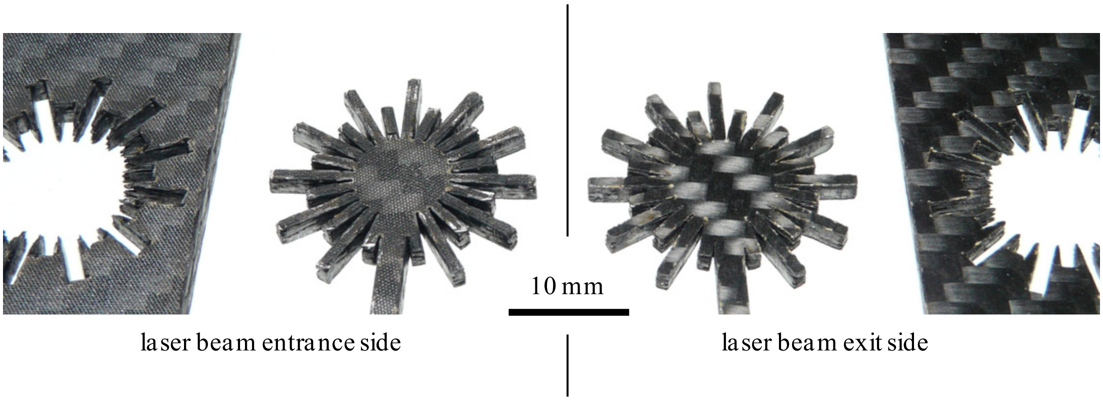

Fig. 13. Reference piece cut by laser

6. Future Work

After investigating the improvements in the cut quality by adding soot to the resin, further work should be done by testing the influence on the fatigue strength of the CFRP. These investigations are part of the research project Elite, where the main focus is on lightweight construction. In the course of this new processes for cutting and joining of CFRP are developed. Thereby a responsibly usage of resources is examined. Within that project also the machining of CFRP looked at closer. It will be compared with other techniques such as milling and water jet cutting.

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