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Influence of remote laser cutting on the fatigue strength of CFRP

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Abstract

For the production of components made from carbon fibre reinforced plastics (CFRP), the cured parts need to be trimmed to the final outline. State-of-the-art technologies for this processing step are either milling or abrasive waterjet cutting. Although remote laser cutting is a wear free process, it is not yet used in industrial application. Recently, the heat affected zone (HAZ), resulting from the ablation of the material by the laser radiation, has been discussed as a quality criterion related to visible components.

To evaluate the influence of the cut edge on the fatigue strength, dynamic tensile tests were performed with an open hole specimen geometry. Noticeable higher values of the fatigue strength were observed using remote laser cutting compared to waterjet cutting.

The specimens manufactured by remote laser cutting endured a higher average number of load cycles and showed a lower deviation of the fatigue strength than the control samples cut by a waterjet. Before fracture, only the laser cut samples showed a noticeable decrease of stiffness which could be relevant for purposes of structural health monitoring. Furthermore, the fracture patterns of the laser cut samples showed characteristics of a matrix based failure, whereas the waterjet cutting led to fibre fractures.

This study confirms that remote laser cutting is suitable for structural CFRP parts which are exposed to dynamic loads.

Keywords: CFRP, laser Cutting, Machining, Fatigue, Strength, Tensile, Waterjet Cutting

1. Motivation

Compared to cars with conventional drive trains, electric cars currently face limitations regarding range and driving dynamics. With the focus on the load-bearing structure, the mass of the vehicle needs to be reduced through the use of materials with a high stiffness to mass ratio. Carbon fibre reinforced plastics (CFRP) have already demonstrated their potential for light-weight construction in motor sports. Large scale and cost effective production is in high demand for commercial cars. In the manufacturing process of CFRP parts it is necessary to cut the outer contour. Remote laser cutting is a capable process because it meets the requirements of the industry concerning contour-flexibility and wear free ablation.

In this work the influence of the cut edge from remote laser cutting on the fatigue strength was evaluated. Abrasive waterjet cutting was chosen for comparison. By using a dynamic tensile test procedure with an open hole specimen geometry, a stress concentration on the edge was achieved. When the laser based ablation was performed with a multiple pass strategy, the width of the heat affected zone (HAZ) could be reduced by increasing the delay time between the ablation passes [1]. By testing at two load levels, the relation between cut properties and fatigue strength was compared and interpreted in regard to the stiffness

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measurement and the fracture patterns. Finally, the effective cutting speed was calculated as a function of the contour length for different laser cutting strategies.

2. State of the Art

Until now, CFRP parts are mainly produced in processes based on resin infiltration or pre-impregnated textiles (Prepreg). After curing, the raw part has protruding edges which subsequently need to be trimmed. In this section a short overview on the processes abrasive waterjet cutting and laser beam cutting is given and fatigue testing as a method for the evaluation of the cut edge is described.

2.1. Abrasive waterjet cutting and milling

Waterjet cutting is well established in industry [2]. Hence, this process was used as a reference by KRISMAN [3] for cutting thermoplastic composites and by SHANMUGAM ET AL. [4] in relation with duroplastic CFRP. The material is removed by abrasive particles in a high pressure waterjet. The waterjet is focused by a nozzle which is in contact with the abrasive particles. Thus, this part wears out, which causes a successive decrease in cut quality.

In comparison, the edge quality for milling depends even more on the tool wear, caused by the abrasive character of the carbon fibres. As a result, fibre pull out can be observed [5].

For both cases thermal damage of the cut edge is not an issue due to the material removal by mechanical cutting. In waterjet cutting, delamination is more likely to occur, especially at piercing operations or at varying laminate properties [6]. Waterjet cutting is economic, results in a cut edge with a high quality, and is almost independent of the material´s anisotropy [7].

2.2. Thermal ablation by laser radiation

With the development of high power laser beam sources another cutting tool came into consideration: Thermal ablation with laser radiation [8]. For industrial application, a high intensity and a high average power is required for productivity reasons. Thus, high power lasers in the infrared spectrum are commonly used [9]. These systems are easy to set up because the laser beam can be guided to the optics through an optical fibre. Using fixed optics for focusing the laser radiation onto the work piece, the movement of the laser spot is controlled by a positioning system e. g. an industrial robot [10]. Hereby the kinematics limit the dynamics of positioning of the focal spot. In contrast, scanning optics allow to deflect the beam rapidly [11]. Hence, the required energy to cut the workpiece can be applied either in a single pass or by multiple passes. When using multiple passes, the heat affected zone directly depends on the time between the rescans of the part contour. This allows to reduce the HAZ to a minimum average width of 50 µm. Only pulsed systems could cause a smaller HAZ at a noticeable lower productivity [12]. In previous studies with a continuous wave (cw) laser source, it was not possible to further reduce the HAZ below 50 µm [1], and a compromise between cutting speed and reducing the HAZ needs to be found.

2.3. Fatigue testing of CFRP

Structural parts are usually exposed to dynamic loads. To evaluate the influence of the HAZ on the fatigue strength, an appropriate testing method is required [13; 14]. Dynamic testing with standard tensile specimens (ASTM D3479 / D3479M-12) stress the specimens over the whole width. Hence, these tests are not valid to evaluate the edge [15]. Further trials related to the test procedure in DIN ISO 50100 have shown a large spread. The fracture frequently occurred near the clamping, which causes the result to be invalid [16].

To concentrate the stress on the cut edge, an open hole tensile geometry according to ASTM D5766/D5766M-11 is suitable (Figure 1). The specimen's outer edges need to be ground and only the centred hole is machined with the considered process. The dynamic load $F_{z,dyn}$ is applied in the longitudinal direction of the specimen geometry which corresponds to the main fibre direction. The stress concentrates on the outline of the hole due to the notch effect. Thus, the properties of the cut edge show a large impact on the failure behavior.

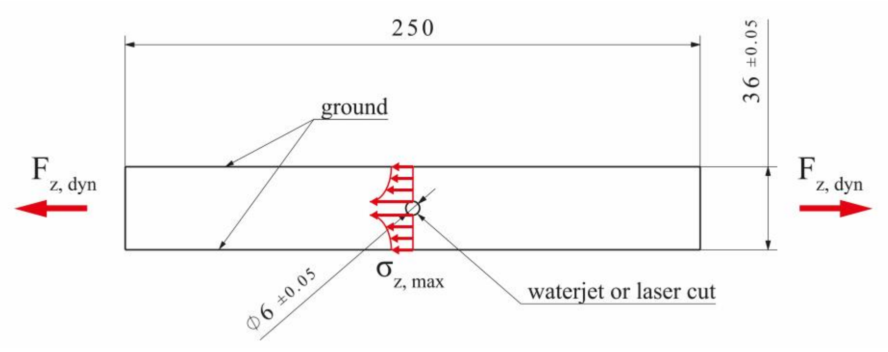


Figure 1: Specimen geometry based on ASTM D5766/D5766M-11; the dynamic load $F_{z,dyn}$ is applied in the longitudinal direction; the arrows at the critical plane indicate the qualitative distribution of the maximum stress $\sigma_{z,max}$

3. Approach and Objectives

The main objective of this work is the assessment of remote laser cutting for contour trimming of dynamically loaded structural CFRP. Therefore, the influence of the edge properties on the dynamic strength is evaluated. Abrasive waterjet cutting was chosen as a benchmark. Depending on the processing parameters, laser cutting affects the width of the HAZ or even causes edge defects. By performing dynamic tensile testing with an open hole geometry, the load is concentrated on the cut edge, improving the sensitivity of the test. The number of load cycles is a major criterion and will be discussed. The loss of stiffness is monitored and interpreted in the context of the fracture patterns. Using the result of fatigue tests, the necessity of reducing the HAZ is discussed related to the consequence on the effective cutting speed.

4. Experimental Setup

4.1. Remote ablation cutting of CFRP

Thermal ablation of CFRP requires a spatially high focused energy input. While the epoxy resin is vaporized at a temperature of 300 °C, the temperature for the sublimation of the carbon fibres is higher than 3000 °C [17]. At the same time, the fibre has a high heat conductivity. Thus, the surrounding matrix is damaged due to the heat affection. To reduce this effect, a fast input of the energy is required to ablate the carbon fibres before the heat is conducted into the remaining material, causing a larger HAZ. To maintain the comparability with previous experiments described in [16], the same machining parameters were chosen, as shown in Table 1.

Table 1: Processing parameters

constant parameters	value				unit
wavelength λ	1068				nm
beam characteristics	single mode				-
focal diameter d_f (86 %)	58				µm
Rayleigh length z_R (86%)	1.2				mm
working distance w_d	365				mm
laser power P_L	3				kW
variable parameters	**value**				**unit**
scanning speed v_s	6000			150	mm/s
number of passes p	27			1	-
delay between two successive passes t_d	300	200	100	0	s
average width of HAZ w_{HAZ}	147	183	231	1210	µm

During the delay between two successive passes, the heat is conducted from the cut edge into the surrounding material, causing less thermal damage on the fibre-resin-interface and on the resin itself.

The material properties of the CFRP are shown in Figure 2. The CFRP was made from a Prepreg with blackened matrix resin. The quality of the cut was improved by adding carbon black to the resin, which results in an increase of the absorption of the infrared radiation in the resin. A complete cut through the specimen plate with a thickness of 2.1 mm is achieved by p = 27 passes at a scanning speed of v_s = 6000 mm/s. The time delay t_d was varied in three steps from 100 to 300 ms. Referring to the single pass strategy, which is used in combination with fixed optics, two samples were cut with a single pass at a speed of 150 mm/s. The reference samples were manufactured with abrasive waterjet cutting. The process was carried out without a variation of the cutting parameters and with reduced pressure for piercing in order to avoid delamination.

	CFRP properties
fabrication process	Prepreg
plate thickness	2.1±0.1 mm
laminate lay-up code	[0/90F6]
layer weight	150 g/m^2
matrix additive	carbon black

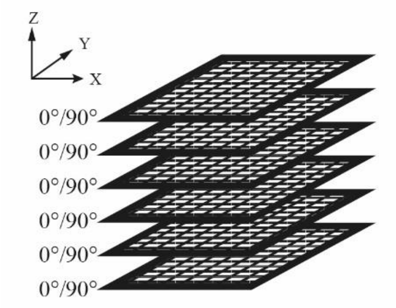


Figure 2: Properties of the CFRP

4.2. Specimen geometry

The specimen geometry shown in Figure 1 was produced according to ASTM D5766/D5766M–11. The hole in the centre of the specimen was manufactured with the processes described above. The outer surfaces were first cut with a waterjet and then ground to the nominal width of 36 mm. The grinding process was needed to eliminate the influence of the outer surface on the results. According to the standard, the orientation of the 0° fibres of the CFRP was aligned in the longitudinal direction of the specimen geometry.

4.3. Open hole tensile testing

The adjustment of the dynamic load is crucial in order to achieve stress cycles around 10^6 per samples. Therefore, quasi static tests are necessary. Knowing the average maximum strength of the samples, the dynamic load level can be adjusted accordingly.

Using each three of the waterjet and the different multiple pass laser samples, the static strength was found to be between 384 MPa and 497 MPa with a mean value of 452 MPa. In the first series of tests, the dynamic load was set to 90 % of the static strength, 405 MPa. A second series was performed at 87 % at 395 MPa. In order to have a valid result for the multiple pass laser samples, five samples were used for each parameter according to ASTM D5766/D5766M-11. For reference purposes, three waterjet specimens were used.

5. Results and Discussion

5.1. Fatigue testing

The dynamic strength of the samples at a load level of 405 MPa is shown in Figure 3. The abscissa represents the stress cycles in a logarithmic scale. The average width of the HAZ of the laser cut specimens is given in Table 1 for a delay time of 300 ms, 200 ms, and 100 ms. The specimens cut by waterjet failed between n=10 and 2.0×10^5 stress cycles. The most durable sample failed in the same range of stress cycles as the weakest laser cut sample. In contrast, the laser cut specimens showed a significantly lower variation. At a delay time of 300 ms, between 1.5×10^5 and 1.7×10^7 stress cycles were achieved. Lower delay times led to a decrease of the scatter. The minimum value of the dynamic strength for a delay time of 200 ms was 4.1×10^5 stress cycles and in the case of 100 ms 3.4×10^4 stress cycles were achieved. It is noticeable, that four out of five samples exceeded 10^6 load cycles, when a delay time of 200 ms was used. Even though extensive studies were performed on how to reduce the HAZ, the results of the fatigue testing indicate, that a larger HAZ is preferable if a small variation of the dynamic strength is desired. Further confirmation of these conclusions can be drawn from the second series of fatigue experiments.

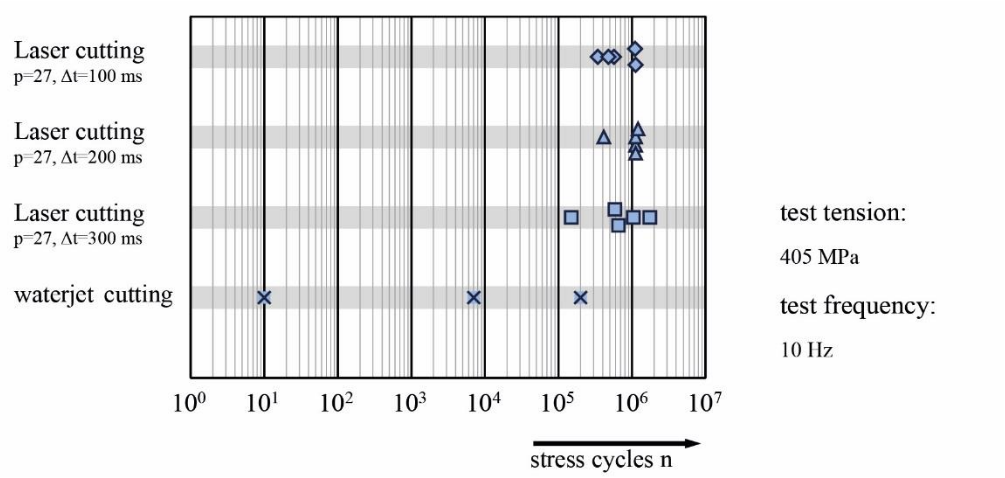


Figure 3: Open hole tensile tests at a dynamic load $F_{z,dyn}$=405 MPa

For an evaluation at an increased number of stress cycles, the dynamic load was reduced to 395 MPa, which is 87 % of the average quasi static tensile strength. As shown in Figure 4, one waterjet specimen broke after 6 stress cycles, the others at 3.2×10^5 and 7.2×10^5.

For laser cutting with a multiple pass strategy, the majority of the samples failed in the range between 8.1×10^5 and 2.0×10^6 stress cycles. Two outliers were observed; one with a time delay of 300 ms broke after one load cycle; the other one with a delay time of 200 ms broke after 1.4×10^4 cycles. As mentioned before, the quasi static strength was lower than the dynamic load in some cases of this series. A possible reason for the early breakage of these specimens is the fact that CFRP is an anisotropic material with a wide variation of the material properties. The highest repeatability is obtained at a delay time of 100 ms. All results showed a small variation.

In addition, two specimens made with single pass laser cutting were examined. Despite of the wide heat affected zone (cf. Table 1), both single pass specimens endured more than 10^6 stress cycles. A further investigation is indicated because these specimens broke after an unexpected number of cycles even if they had a significant thermal damage of the cut edge.

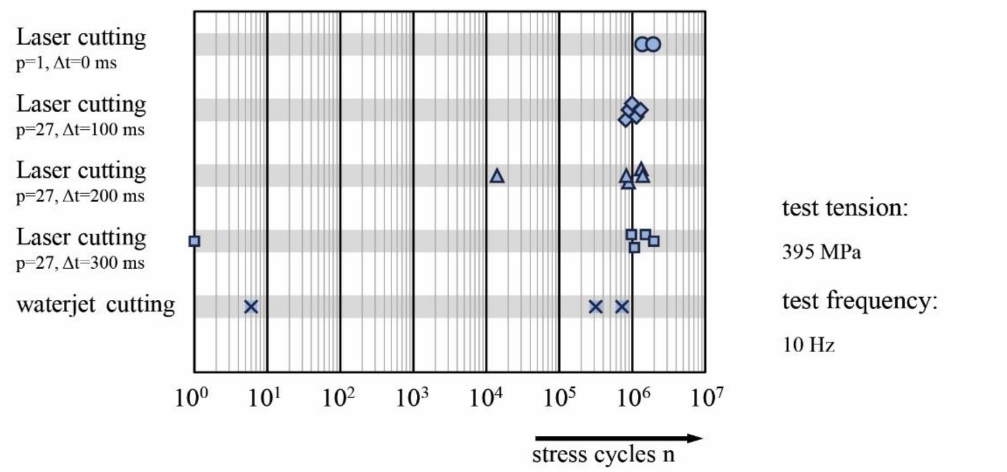


Figure 4: Open hole tensile tests at a dynamic load $F_{z,dyn}$=395 Mpa

5.2. Stiffness measurement

The stiffness of the specimens was measured during the experiments. All waterjet samples showed a similar trend in the stiffness graph. In Figure 5 the abscissa shows the stress cycles in a logarithmic scale and the stiffness is on the ordinate as the ratio between applied force and displacement. For waterjet cutting, the corresponding blue line has a small decrease of the stiffness during the first 10 load cycles, followed by more than 10^5 load cycles without a noticeable decrease. Whithin one decade before the sudden break, only a slight decrease of stiffness can be observed.

For laser cutting, the stiffness trend of the specimens with a small HAZ did not differ significantly compared to those specimens cut by waterjet. Related to specimens with a wider HAZ, a typical stiffness course was observed.

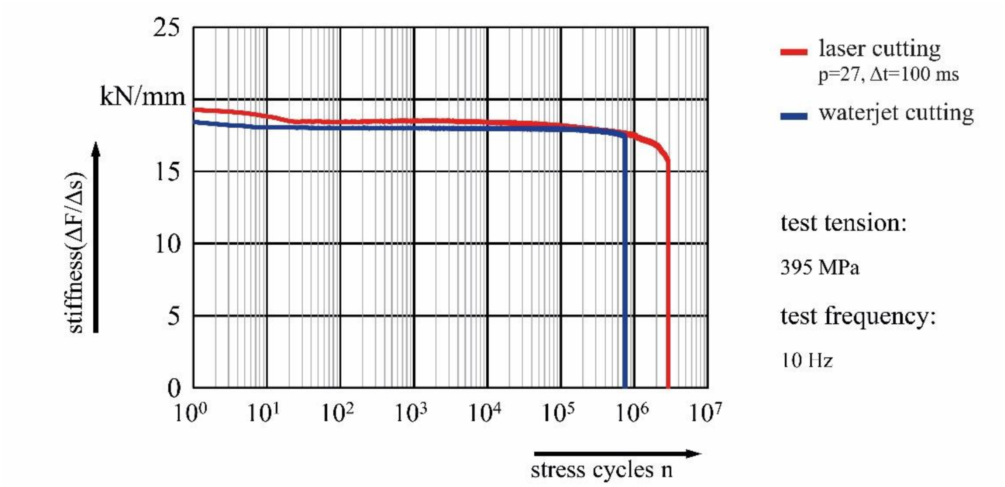


Figure 5: Typical stiffness trend for waterjet and laser cut specimens

The red line in Figure 4 is characteristic for laser cutting with a delay time of 100 ms. With a larger decrease in stiffness during the first decade, a constant level of stiffness was measured for about three decades. In the last two decades before breakage, the stiffness is declining by approximately 3 kN/mm. This behavior could be useful for structural health monitoring, as failure might be predicted from the decrease in stiffness of more than 10% compared with the initial value.

5.3. Fracture patterns

An interpretation of the stiffness behavior and the variations in the number of stress cycles can be obtained by comparing the different fracture patterns, as depicted in Figure 6 for a stress level of 405 MPa. The samples which endured either the low or a high number of cycles are shown for waterjet cutting and laser cutting with delay times of 300 ms and 100 ms, respectively. A straight fracture is observed for the sample cut by waterjet which broke at a low cycle number, without a noticeable delamination of the carbon fibre rovings (6.1). In contrast, the specimens with a high number of stress cycles made with laser cutting and a delay time of 100 ms broke with a wide delamination area (6.6) which could be observed to be gradually developing before the failure of the specimens by video recording. The reason for this behaviour can be described by Figure 5. It can be assumed, that delamination is the reason for the loss of stiffness, which mainly occours related to a wider HAZ. Hence, the fracture of waterjet cut samples is abrupt and straight-lined.

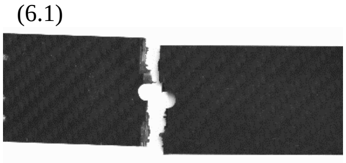
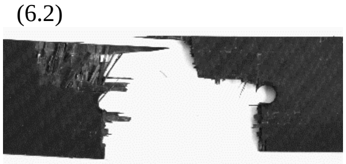
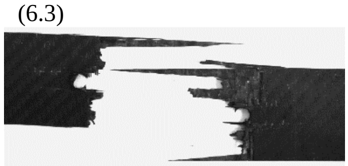
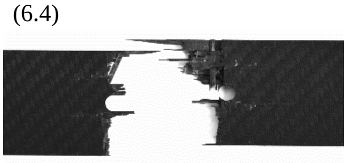
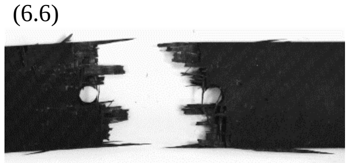
	waterjet cutting	laser cutting, p=27, t_d=300 ms	laser cutting, p=27, t_d=100 ms
minimum fatigue strength	(6.1)  n=10	(6.2)  $n=1.4\times10^5$	(6.3)  $n=3\times10^5$
maximum fatigue strength	(6.4)  $n=2.0\times10^5$	(6.5)  $n=1.7\times10^6$	(6.6)  $n=1.1\times10^6$

Figure 6: Fracture patterns for extremal stress cycles at 405 MPa

Comparing the fracture patterns of each machining method with both the minimum and the maximum cycle number, a higher occurrence of straight break lines was mostly found for samples which broke at lower cycle numbers. Moreover, the break patterns of waterjet cutting were mostly characterized by a straight fracture edge. The laser cut samples with a small HAZ at a delay time of 300 ms show both characteristics; they break either in a straight line or with a significant delamination.

At a delay time of 100 ms, delamination dominated fractures can be observed in correlation to a high number of stress cycles before breakage and stiffness fading due to delamination.

As an explanation for these discrepancies, the notch effect was taken into account. The edge of the centered hole, which is under concentrated stress, was considered as the initial point of fracture. It can be assumed, that the thermal influence reduces the stiffness of the cutting edge and stress peaks are dissipated more evenly in the critical plane of the specimens.

5.4. Effective cutting speed

At this point, the effective cutting speed can be discussed after the fatigue strength for the different cutting strategies was examined. On-the-fly cutting cannot be applied on contours exceeding the scan field, because the process is sensitive to a varying angle of incidence. Hence, several static positions of the scanning optics are necessary for the processing of each contour section.

The delay time used for a small cut length in the experiments can obviously be used for cutting the remaining parts of a large contour within the scan field. Hence, the actual wating time between the rescans is the difference between delay time and scanning time. Expression 1 specifies the effective cutting speed v_e. A distinction into two cases can be made, depending on the contour length l_c within the scanfield. Figure 7 shows the graphs of this function $v_e(l_c)$ for different values of the delay time t_d and the scanning speed v_s. For comparison purposes, the cutting speed of the single pass experiments is marked with a grey line. For longer contours, a higher effective speed can be achieved with a multiple pass strategy.

$$v_e(l_c) = \begin{cases} v_e = \dfrac{l_c}{t_d \cdot (p-1) + \dfrac{l_c}{v_s}} & \text{if } 0 < l_c \leq \dfrac{v_c}{p} t_d \\ v_e = \dfrac{v_s}{p} & \text{if } \dfrac{v_c}{p} t_d < l_c \end{cases} \quad (1)$$

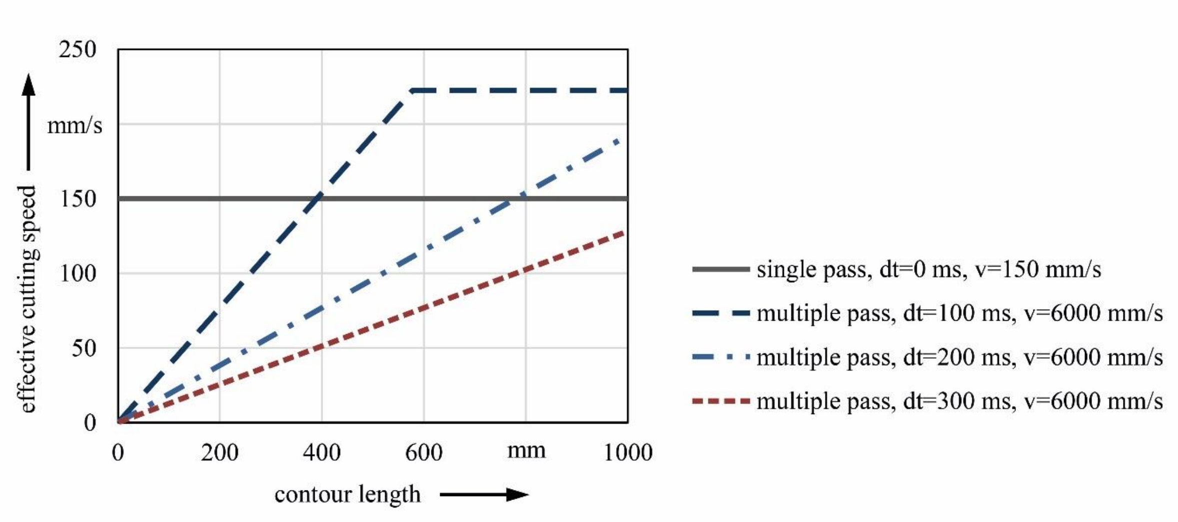


Figure 7: Effective cutting speed as a function of the contour length for the single pass and the multiple pass strategy

6. Conclusions

Tool wear and delamination are critical aspects, when milling or waterjet machining is used for cutting CFRP. Remote laser cutting is a promising alternative. The cutting strategy is the key to different edge qualities. By using a delay time between the rescans in multiple pass cutting, the average width of the heat affected zone could be adjusted. By performing open hole tensile tests, it could be shown that the heat affected zone is not in contradiction with a high dynamic strength. As a consequence, regarding the fatigue strength, remote laser cutting of CFRP can be carried out with a high effective cutting speed. On the one hand milling and waterjet cutting are able to provide a visibly high edge quality, on the other hand the “tool” laser is wear free and the process of laser cutting is an appropriate alternative for machining CFRP for the use under high dynamic loads.

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