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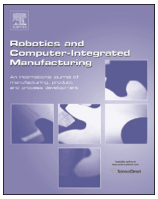

Comparison of surface roughness quality obtained by high speed CNC trimming and high speed robotic trimming for CFRP laminate

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ABSTRACT

This paper proposes an experimental approach for evaluating the surface roughness of the CFRP parts produced by high speed CNC trimming and high speed robotic trimming under various cutting conditions. A comparison is made between the surface roughnesses obtained by the two processes. The results obtained show that, the measured profiles obtained from high speed robotic trimming are dominated by a large trajectory deviation, as compared to machine tool trimming results. After the trajectory deviation effect is discounted, the results show that for the $+45°$ ply orientation, the surface quality obtained through high speed robotic trimming is similar to what is obtained with the CNC machine. Furthermore, a significant relationship was observed between the surface quality and the ply orientation, whatever the machining process and the cutting conditions employed. The $-45°$ ply orientation represents the worst case in terms of surface roughness, whatever the machining process. It is 4 times higher compared with that of $+45°$ ply orientations,

The results also show that the effect of cutting conditions on surface quality is significant for both machining processes tested.

1. Introduction

Carbon Fiber Reinforced Polymers (CFRPs) are gaining ever-wider acceptance in aerospace applications, thanks to their desirable mechanical and physical properties. CFRP parts are usually produced by molding or near net shape; in some applications such as wings and fuselage panels, trimming, milling, and drilling are still required to bring CFRP parts to their final shapes and sizes. A more detailed study on machining composite materials can be found in [1–4].

Trimming of carbon fiber is generally done with the CNC machine tool; however, machine tool has a restricted working area, is less flexible than robot, its high up-front costs, and its higher operating costs. Thanks to their adaptability, programmability, high dexterity and good maneuverability, industrial robots offer cutting-edge and lower-cost solutions than machine tools to bring molded CFRP parts to their final shapes and sizes. These robots have indeed already been introduced to many industrial applications, including welding, painting and assembly, and have produced excellent results. They are relatively cheaper as compared to the machine tool, are flexible, and have a large working envelope. However, under a heavy cut, and given their serial structure, such robots are susceptible to errors of many sources, with the most essential being geometrical errors, servo errors, as well as the end-effector deflections caused by the cutting forces and torques [5–11]

During the trimming of CFRPs, unstable cutting conditions cause many effects on the surface quality of finished products. To characterize the results of CFPR trimming, several aspects must be considered, including surface damage, subsurface damage and surface roughness. The latter could have a significant impact on the assembly quality, and is therefore a good indicator of machining performance. It must be noted though, that in the case of metal working, for which the roughness is easily measured with repeatability, it may be more difficult to evaluate this surface quality parameter for CRFP laminates. This difficulty is due to the non-homogeneity of the materials involved, as well as the complexity surrounding the retrieval of the adequate statistical indicator.

Over the last decade, many studies have considered the roughness of machined surfaces of fiber reinforced plastics, with a view to predicting the roughness from machining conditions. Boudelier et al. [12] proposed a methodology to optimize process parameters for trimming applications. Their methodology was then applied in the composite trimming process, with a diamond abrasive cutter. They found that grit size and feed per revolution are key factors in ensuring required surface roughness and

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improving productivity, respectively. Davim and Reis [13] referred to the ANOVA method and the design of experiments to predict the surface roughness parameters R_a and R_z with respect to the end-milling machining conditions of glass fiber reinforced plastic (GFRP). They selected three cutting parameters as variables: the feed rate, the cutting speed and the depth of cut. Their studies led to the conclusion that the roughness R_z increases with an increased feed rate and decreases with an increased cutting velocity. Again, Davim and Reis [14] conducted a similar study, and arrived at the same conclusions regarding the machining of carbon fibers. Similar results were also found by Palanikumar [15], who used the Taguchi method and Pareto ANOVA analysis to study the average roughness parameter R_a during the turning of GFRP composites. An approach for optimizing the machining parameters on milling glass-fiber reinforced plastic (GFRP) composites was proposed by Jenarthanan and Jeyapaul [16]. They conducted milling experiments based on the Taguchi technique, using a solid carbide cutting tool. The machining parameters such as the spindle speed, the feed rate, the helix angle and the fiber orientation angle were optimized by multi-response considerations, namely, surface roughness, delamination factor and machining force. They found that a lower fiber orientation angle, a lower helix angle, a moderate spindle speed and a lower feed rate constitute the ideal conditions for machining GFRP composite plates. Slamani et al. [17] studied the machinability of autoclave-cured 24-ply CFRP laminate under varying cutting conditions using a CVD diamond coated carbide tool with six straight flutes. They found that the optimum cutting conditions are achieved at lower feed rates and higher cutting speeds. Palanikumar et al. [18] studied the influence of cutting conditions on surface roughness parameters in the turning of glass fiber reinforced composite materials. They found that the surface roughness increases with an increase in the feed rate, and almost decreases with an increase in the cutting speed. They also developed empirical models to correlate the machining parameters with surface roughness.

More recently, Zhang et al. [19] studied the effect of cutting parameters such as cutting velocity, cutting depth, cutting width, as well as feed rate on the surface roughness of CFRP using PCD tools. Unlike what was found in previous results, they found that the cutting depth has the most significant effect on surface roughness, followed by the cutting velocity, and the cutting width, while the feed rate has little effect. Palanikumar [20] built a prediction model based on the fuzzy modeling of R_a and R_t. The same method was used by Rajasekaran et al. [21] for the turning of carbon/epoxy composites. For both studies, the authors neglected the effect of the fiber orientation. However, other studies have considered the ply orientation as a variable in their analysis of the surface roughness. Eriksen [22] found that surface roughness was independent of fiber orientation, but only for short fibers. In another study, a mathematical model with regression analysis and ANOVA was realized by Palanikumar and Davim [23], leading to the conclusion that a low fiber orientation angle generates a better surface finish. This effect was confirmed by Sarma et al. [24] in a study in which the roughness parameter R_a was evaluated in a second-order model, based on four machining parameters. The roughness was measured with a vision system using a digital camera, in order to avoid contact with the machined surface. Their studies were conducted on GFRP, and did not take into account any negative fiber angles. However, Jahromi et al. [25] studied the effects of all fiber orientations on surface damage occurring during the machining of unidirectional composites. Their conclusions showed the worst case to lie between an 80° and a 135° fiber angle, and the best case at 0° or 180°. Chatelain et al. [26] used a PCD tool comprised of two straight flutes to trim 32-ply carbon fiber laminates. They found that the fiber angle is an important parameter affecting the roughness profile. They also showed that each ply orientation has its own “typical” profile, regardless of machining conditions. In addition, they showed that the cutting speed effect was not as significant as the feed rate effect on surface roughness, but that a higher cutting speed leads to better surface finishes in most cases.

Regarding the effects of cutting parameters on the surface roughness, most studies conclude that the surface quality is improved with a low feed rate, high cutting speeds and low depths of cut. The feed rate appears to be the most significant factor of influence on the surface finish, followed by the cutting speed, while the depth of cut has less of an effect than the two others.

In general, the authors base their analyses on statistical indicators such as R_a, R_t or R_z, which are efficient for isotropic metallic materials. In the case of metallic materials, the probe location has a low impact on the measurement results. That is not the case for composite materials, where the location of the probe with respect to the ply orientation can significantly affect the measurements. It is therefore very important to pay particular attention to the probe location during surface roughness measurement of composite materials. Furthermore, due to the anisotropic nature of the CFRP and influence of fibre direction on workpiece damage, many studies [12,27,28] recommended that 3D roughness parameters (areal parameter Sa, St, etc.) were preferable for characterising machined surface quality in CFRP workpieces.

On the other hand, the majority of the studies on the surface finish quality of FRP are on CNC machining; with the exception of a few papers [8,29], the number of studies on robotic trimming of CFRPs is quite limited. Furthermore, the surface finish quality of CFRP parts obtained by robotic machining has never been investigated. In fact, this is one of the major issues in robot machining that must be addressed in order to extend the technique to more applications. In this study, the effects of cutting parameters (cutting speed and feed rate) and ply orientation on the surface roughness of CFRP laminate materials during high speed robotic trimming will be thoroughly analyzed based on the raw signals of the profilometer measurement system. Then, a comparison will be made between the surface roughness obtained by a high speed robotic trimming process and that obtained by a high speed CNC machining process. The occurrence of delamination will be also discussed in this study.

2. Material and methods

Dry machining tests were performed on 305 mm × 305 mm CFRP laminate plaques using two different manufacturing processes. The first process was high speed trimming with an industrial robot. A six-axis KUKA KR 500-2 MT industrial robot mounted on a 4 m linear rail, manipulating a heavy HSD Mechatronic ES 789 spindle, and delivering spindle speeds of up to 26,000 rpm, was used to perform the experiments (Fig. 1). The robot was programmed using the CAD/CAM Robot-master software, and could handle a 500 kg payload.

The second manufacturing process is high speed trimming with a CNC machine tool. For this process, a three-axis HURON K2 × 10 machine tool (Fig. 2) was used.

The laminates used in the machining tests were prepared in a controlled aeronautical environment using pre-impregnated technology. The stacks were autoclave-cured, and the plies were oriented such as to ensure that the laminate had quasi-isotropic properties. The 24-ply laminate was 3.68 mm thick, with a fiber volume fraction of 64%. The ply orientation lay-up of the laminate is presented in Table 1.

Before the trimming test was started, the laminates (Fig. 3) were pre-drilled for tightening on a machining fixture. The predrilling was necessary for screwing the laminate to the fixture, in