Experimental Study on the Influence of Drill Wear in CFRP Drilling Process

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Abstract
Drilling of Carbon Fiber Reinforced Plastics (CFRPs) is a frequently practiced machining process in industry for assembling different parts in order to obtain complex structures. The aim of this research is twofold, addressing both the understanding of the delamination phenomenon and the generation of an extremely high wear on drill bits which decreases cutting performances. Several experiments have been carried out in order to exactly define how the drilling methodology and the cutting parameters influence the quality of the machined part, in terms of damage of the composite internal structure. The cutting process has been monitored by means of a force sensor and then correlated with drill wear state and push out delamination. Analysis of data carried out in this study has shown that an increase of the cutting speed accelerated the tool wear by the continuous friction of the drill bit on the carbon fibers. This phenomenon, leading to a rapid change of the edge geometry, can be prevented by regulating the drilling parameters using a fuzzy-logic-based adaptive control which is proposed in this paper as well.

Keywords: CFRP, Drill Wear, Delamination

1 INTRODUCTION

Machining Fiber Reinforced Plastics (FRPs) is a rather complex task owing to their heterogeneity, heat sensitivity, and to the fact that reinforcements are, in most cases, extremely abrasive. For this reason machining by conventional methods should be adapted to reduce thermal and mechanical damages.

Even if the breakage of fibers should be avoided in order to prevent a decay in mechanical properties, in the aerospace industry, drilling is frequently practiced and accounts nearly 40% of all the non-metal removal operations [1]. This is due to the need for assembling different parts by bolted or riveted joints when is not possible to obtain complex structures by a single forming process. As a matter of fact, drilling is significantly affected by the tendency of these materials to delaminate and the fibers to bond from the matrix under the action of machining forces.

Among all different drilling techniques (including non conventional ones like Laser Beam Machining and Water Jet Machining) conventional chip removal by twist drills is still the most frequently applied for secondary machining of FRPs owing to the fact that manufacturing these kind of materials can be actually considered a handicraft process.

2 DRILLING OF FIBER REINFORCED PLASTICS

Drilling of FRPs represents one of the most interesting challenge in machining processes and has been deeply investigated in the past 10 years as demonstrated in [2].

Many authors [3-5], when reporting about drilling of laminated composites by conventional tools, have shown that the quality of the machined surfaces is strongly dependent on the cutting parameters, tool geometry and tool material. An inappropriate selection of these parameters can lead to unacceptable material degradation, such as fiber pull-out, matrix cratering, thermal damage and delamination. Feed rate significantly influences the integrity of the composite since the use of high values may induce crack formation around the exit edge of the hole.

The non secondary effects of cutting parameters on matrix degradation in drilling carbon/epoxy composites where studied in [6]. It was proven that thermal degradation of the epoxy resins reduces its capability of transferring shear stresses between different layers of the laminate.

Researches on this topic have been devoted twofold to better understand the damage formation during the cutting [7,8] by experimental tests and to develop theoretical models [9] to predict the critical value of the thrust force which produces delamination. Such knowledge was used in [10] to develop an intelligent method, based on fuzzy logic, enabling the control of a drilling machine with thrust force feedback to maximize productivity with minimum damage.

Due to the complex nature of the drilling process of FRPs several experimental efforts [11, 12] analyzed the thrust force, by using neural networks. In this way the complex phenomena leading to the damage of the laminate can be easily traced back to the cutting parameters.

Damage can be then prevented through a real-time monitoring systems able to vary the cutting parameters depending also on drill wear state which strictly affects thrust force. The availability of such intelligent control schemes should represent a large advancement in the efficient drilling of FRP parts.

3 EXPERIMENTAL DETAILS

Delamination damage in composites is then caused by excessive drilling force at critical stages during the process. This suggests that damage can be prevented through real-time monitoring of process variables such as the thrust force, the tool position relative to the workpiece and the drill wear state.

At this purpose the present research was structured as follows:

- Step 1: concerning the correlation of thrust force, wear and delamination measurements with the cutting parameters used in the experiments.
- Step 2: linking between drill wear state and damage of the laminate at the exit of the drill bit.
- Step 3: proposal of a fuzzy logic adaptive control, which made use of simple rules based on the adjusting the feed rate.

The workpiece material used in these tests was CFRP laminate (8mm thickness), obtained by the superposition of 0/90° twill fabric layers constituted by ultra high modulus fibers (E=294GPa, σ_U =4900MPa). The pre-preg fabric had a volume fraction carbon fiber/epoxy matrix of about 42%.

As far as the type of twist drill is concerned, HSS twist drills have been used (20° helix angle, 118° point angle, reduced web) thus reducing the number of holes necessary to appreciate a measurable wear and then to minimize the test layout.

Tests were performed on a CNC machining center with a maximum spindle speed of 4000 rpm, while a Kistler dynamometer 9257 B was used to measure thrust forces during the drilling and monitor the effect of the tool on the composite damage.

3.1 Drill wear measurements

A preliminary analysis on worn drills, performed by an optical microscope, showed that the chip removal of CFRPs induced a different tool decay from that caused by drilling of metals. Main characteristics of this drill wear process can be summarized into three main points.

- Absence of crater wear: this was due to the powdery consistence of the chip which did not cause any fretting by sliding against the rake surface.
- Rounding of the cutting edges: the abrasive action of the carbon fibers acted mainly on flanks and outer corners of the twist drill, reducing the capability of engraving the workpiece.
- Land wear: the leading edge rubbing against the side-wall was affected by the presence of swelled fibers. This phenomenon of uncut fibers swelling reduced hole diameter once the drill was remarkably worn.

In order to measure flank and outer corner wear with the increasing of machining time, a direct monitoring method has been adopted. Drills at different stages of wear have been placed under an optical microscope and by means of a structured light it was possible to point out the worn area. Measurements in squared millimeters were then carried out by image processing. As far as the land wear is concerned, no remarkable reduction in the drill diameter have been noticed. For this reason the worn area on the drill flanks was retained to be the most representative parameter of tool wear state during the drilling of CFRPs.

3.2 Push out delamination (POD) measurements

Composite damage can cause a remarkable reduction in the laminate mechanical properties due to the possibility of crack propagation.

The drilling process may induce the breakaway of two adjacent fabric layers in whatever point of the laminate thickness, if the thrust force of the tool exceeds the interlaminar cohesion. This phenomenon becomes more critical at the exit of the drill where the uncut thickness offers less resistance, generating the so called Push Out Delamination (POD).

In the present research composite damage was always intended as POD since, starting from the acquired practical experience, this type of failure was much more frequent than crack formation in the bulk thickness of the laminate. The extension of such damage is frequently measured in literature [4] by calculating a dimensionless parameter called Delamination Factor (*DF*) obtained by the ratio of the maximum diameter (D_{MAX}) of the damaged zone to the hole diameter.

$$DF = \frac{D_{MAX}}{D} \tag{1}$$

The previous definition of *DF* can lead to errors when the drill action causes only the swelling of few fibers from the matrix because even if there is no crack formation D_{MAX} has remarkable values thus resulting in high values of the damaged zone. To avoid this incoherence a different index (I_{AVG}) was defined in this paper, enabling better information on the effective extension of the damaged zone by means of a percentage increase of the hole radius.

$$I_{AVG} = \frac{h_m}{D_{nom}/2} = \frac{2A_{DEL}}{\pi D_{nom}^2} \tag{2}$$

In (2) A_{DEL} represents the delaminated area included between the hole nominal edge and the external contour (as shown in Fig. 1) which is obtained by image analysis on an optical microscope.

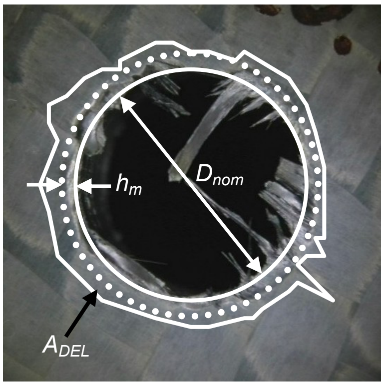

Figure 1: Push out delamination: geometrical parameters.

Similarly to drill wear measurements a structured light made it possible to establish the delaminated surface since the last layers raised up by the tool thrust offered a higher reflection to the light than the non-damaged material.

4 RESULTS AND DISCUSSION

Analyzing several scientific contributes concerning the use of HSS drills in the machining of CFRPs it has been noticed that the influence of the process parameters on the cutting forces and on the wear state was strictly linked to the many different drill shapes and fiber types. For this reason it was difficult to identify a range of commonly used parameters and only few guidelines could be traced back. Thrust force varies depending on the drilling depth and increases with feed rate. It is also remarkably influenced by wear of the cutting edges. In some cases (especially in drilling of GFRPs [2]) it was noticed that an increasing in cutting speed is related with a small reduction in thrust force.

In order to deeply understand the influence of the cutting parameters on tool wear state and delamination, tests were arranged using a three-level factorial design. In this way it was possible to study the complex phenomena by which the drilling process of CFRPs was influenced with a wide range of cutting conditions. These experiments have been conducted with five values of cutting speed (V_C) [20-30-40-50-60] m/min and five values of feed rate (*F*) [0.10-0.15-0.20-0.25-0.30] mm/rev. For each combination of cutting parameters a new drill was used thus avoiding the effect of tool wear.

The influence of drill wear was then analyzed by repeating the same test layout four times with the respective twist drill (for a total amount of $5^2x4=100$holes). In such way it was evaluated the increasing of tool wear during the machining of 4 holes with the same cutting conditions and its effects on thrust force and delamination index (I_{AVG}).

Tests were repeated three times (300holes) allowing to afford repeatability of the acquired data.

4.1 Thrust force

The thrust force signal has the commonly known trapezoidal shape depending on drilling depth. The nearly constant plateau, which reflects the full engagement of the tip represents a measure of the maximum thrust (T) on the workpiece system and was then used as a monitor variable in the present study. The sudden drop can be attributed to the disappearance of the large thrust resistance acting on the chisel edge due to the change of the cutting conditions from plane strain to plane stress, when the uncut plate below drill bit becomes very thin.

As far as the dependence on cutting parameters is concerned it can be noted that, after the machining of the first hole, there are only slight effects of feed rate on thrust force. The increasing of T acted twofold to increase the thickness of the chip (thus resulting in small rises of thrust), and to reduce the drilled length which induce wear on the drill tip. During the machining of the first hole, where new drills were used, this second phenomenon was less significant.

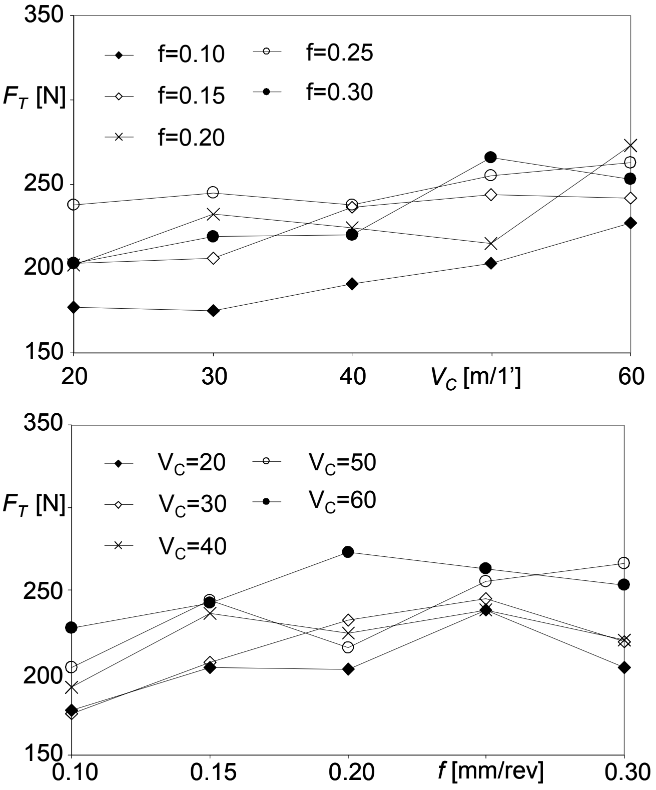

Figure 2: Thrust force after the first hole. Dependence on cutting speed and feed.

In Fig. 3 it can be seen also that after the first hole, even if there was no sensible variation in cutting force increasing V_C up to 40m/min, higher values ([50-60]m/min) tended to generate a rising in thrust action. Since this effect was more evident for low values of F which generate higher drilling lengths, the over mentioned phenomenon can be traced back to the starting up of tool decay.

The thrust force increased with drilled length; this was because the development of tool wear. In this way after the machining of the second hole a 50% increasing in thrust force was globally noticed which reflected the progress of drill wear once the drilling length was doubled. Similar behaviours have been monitored up to the fourth hole, where the variation of tool geometry caused by the abrasive friction of carbon fibers, led to thrusts ranking from 600N to 800N. When twist drills started loosing their original profile, the effects of feed on thrust force were found to be negligible and furthermore lower values of T were acquired when using high feeds ([0.25-0.3]mm/rev), which differed from the common experience. The reason of this particular behaviour can be explained with the lower cutting length generated by these values of feed.

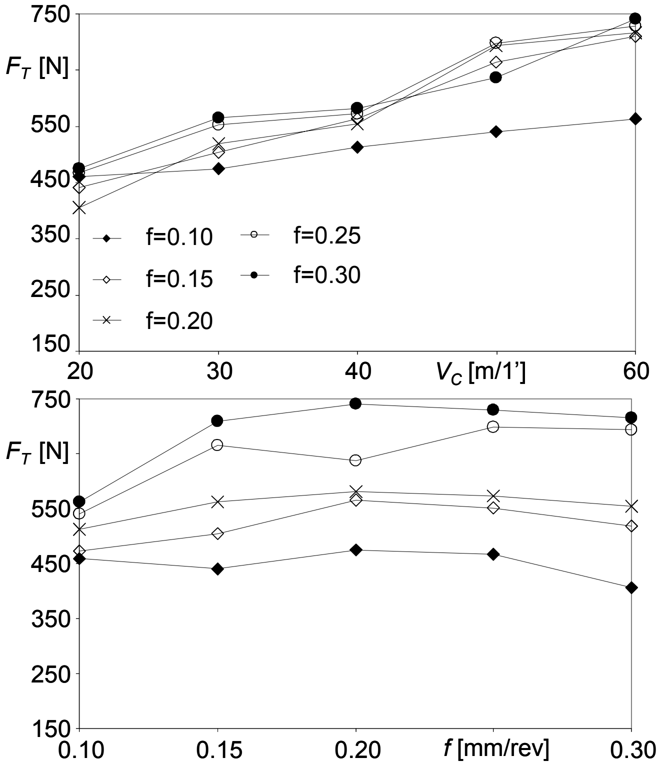

Figure 3: Thrust force after the fourth hole. Dependence on cutting speed and feed.

In fig. 3 it can be seen that there was a strong dependence on cutting speed which was also related to wear increasing.

4.2 Tool wear

As mentioned before, thrust force increased drastically when drill geometry was varied by the presence of wear on the cutting edges. The drill started to worn from the outer corners which had the higher cutting speed and the sharp edge was progressively rounded. The smooth rounded corner reduced the capability of cutting fibers and so buckled and pull-out reinforcements were forced against the hole surface contributing to rise temperature and then tool wear. During tests, chips stuck on the tool could be observed around the worn area especially for high value of cutting speeds.

Measurements have shown that tool wear generally increased both with drilled length (generated by increasing the number of holes or a reduction in feed rate) and the temperature into the cutting zone which caused a decay not only of the composite matrix, but also of the tool material. This rise in temperature was generated by friction of the drill tip on the workpiece and was directly dependent on the cutting speed used in the experiments. The twist drill wear thus depended onto V_C / F ratio. This behaviour can be seen in fig. 4 where measures of worn areas are plotted depending on V_C and F after the machining of the first hole. The above mentioned tendency was also revealed after the fourth hole even if it was more pronounced by the effect of the cumulated drilled length.

The cutting speed was then proved to be a not negligible parameter since it affects tool life, especially during the machining of abrasive materials such as CFRPs.

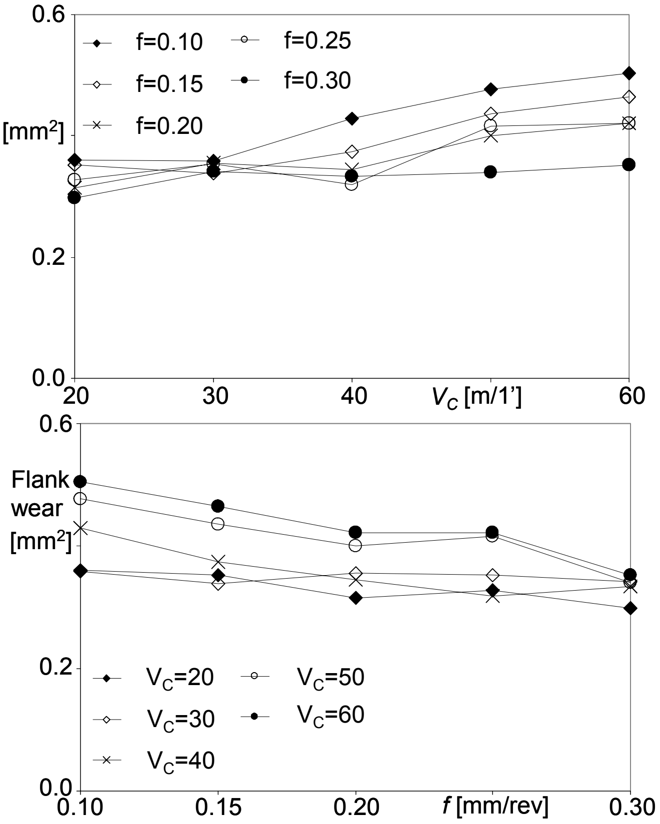

Figure 4: Flank wear after the first hole. Dependence on cutting speed and feed.

The grinding effect of fibers on drill material, especially when high cutting temperatures are developed, lead to an extremely rapid decay which suggested the use of higher hardness tools for industrial purposes.

4.3 Composite damage

The chip formation process during the machining of CFRPs appeared to rely on three material removal mechanisms, namely abrasion, ploughing and cutting. Tests showed that the material removal mechanism changed from cutting to fibers tearing and thermal degradation of the matrix as tool wear increased. Due to the continuous friction a large amount of heat was transferred to the composite material vaporizing the epoxy resin.

Deep investigations have been performed by SEM analysis of the internal surface of the hole, focusing the attention on the last layers where POD began. It was noticed that, at the machining of the first hole, fresh drills were able to engrave the material removing a quite fluent chip. In this case on the internal surface fiber bundles are oriented following the fabric interlacement and the cut ends were found to be still covered of solidified matrix (Fig. 5 a and b).

The effects of the friction between the worn edges and the hole surface became to be evident at the second hole and, after the machining of the fourth one, the material removal mechanism resulted significantly modified. SEM analysis showed in this case that the internal surface was characterized by fibers tear down and absence of matrix which both compromised the hole roundness. When tool wear reached a limit value which hindered to engrave the fibers by shear stress, drill tip became to slide onto the workpiece and reinforcements wear broken by the extremely high tensile stress induced by friction. As a result matrix was degraded by the high temperatures developed during the cutting and then disrupted by the shock wave subsequent to fibers tensile breakage (Fig. 5 c and d).

As far as the Push Out Delamination (POD) is concerned, the above mentioned phenomena made the analysis of the delaminated areas more difficult since the presence of swelled fiber bundles altered optical measurements. Data revealed that thrust force clearly enhance the occurrence of delamination, although the interlacement of fibers in the fabric (warp with a 4mm width) acted to hinder the propagation of cracks. The delamination index ($I_{AVERAGE}$) then assumed maximum values of about [0.25-0.3] corresponding to an increase in radial damage of 1mm which was retained to be a negligible damage which did not interfere with the mechanical strength of the drilled hole.

When fresh drills were used POD was increased by feed rate but was not influenced by cutting speed. As drill length increased the opposite phenomenon was noticed since thrust force became only influenced by tool wear.

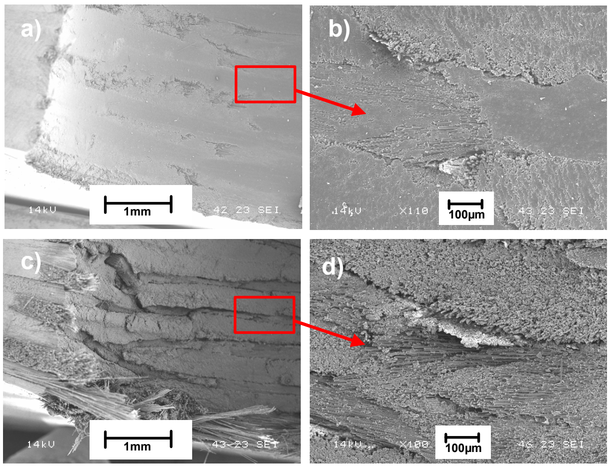

Figure 5: Cross sections of (a) first hole, (b) fourth hole and SEM magnification of the respective machined surfaces.

5 PROPOSAL OF A FUZZY LOGIC CONTROL

Dynamics involved in drilling of composite laminate have proven to be extremely variable at the evolving of wear on the tools. They cannot be modeled mathematically since the dependences on cutting parameter were time varying and nonlinear. To overcome these uncertainties, a theoretical approach of fuzzy-logic based adaptive control is here proposed aimed at minimizing delamination by means of thrust force regulation.

Starting from the acquired knowledge, the fuzzy logic strategy has focused on keeping the thrust force under the threshold value which induces delamination adjusting feed rate. The model should take care of different drill wear states since this has proven to be a distinctive factor into the drilling of CFRPs. For this reason thrust force and drill wear state have been chosen as input variables which directly determine the intensity of push-out delamination. Once the POD has been determined by defuzzyfication process the crisp value was used to extract to correct feed to be set by feedback controller to the CNC machining center.

5.1 Design of membership functions

The first step in establishing the algorithm for POD diagnosis and the strategy for feed rate control was the selection of appropriate shapes of fuzzy memberships μ (or fuzzy sets) for process variables based upon experimental data and observed system behaviors. Four membership functions have been developed respectively for input variables (thrust force and drill wear state), for output variable (feed rate) and for POD which was used as a target variable representing the correlation between inputs and output. The number of linguistic levels (five for each variable) should be large enough to provide an adeguate approximation and yet be small to increase system response and save memory storage. For any variable, such as the output (feed rate) with five linguistic levels (i.e. very slow, slow, moderate, high, very high), an overlap between two adjacent levels is desired to develop the fuzzy effect.

	1		2		3		4		5	
IF	F_T	*W*	F_T	*W*	F_T	*W*	F_T	*W*	F_T	*W*
	VS	VS	VS	S	VS	M	VS	H	S	VH
	S	VS	S	S	S	M	VS	VH	M	VH
			M	VS	M	M	S	H	H	H
			M	S	H	S	M	H	H	VH
			H	VS	VH	VS	H	M	VH	M
							VH	S	VH	H
									VH	VH
THEN *POD* is	VERY SMALL		SMALL		MEDIUM		HIGH		VERY HIGH	

Table 1: Fuzzy rules for Push Out Delamination (POD).

As far as the definition of membership functions is concerned, the reason for choosing trapezoid shape for drill wear state was due to difficulties in quantifying what an exact percentage of toll life corresponds to a certain level of the linguistic variable such as initial, normal, acceptable, severe and failure. The same reasons led to the choice of POD shape. Otherwise, the use of thrust sensor which gave an exact measure of the force without uncertainties led to the choice of sinusoidal shapes. The triangular shape for feed was based on the state-of-the-art experience concerning fuzzy controllers.

5.2 Diagnosis of delamination

The relationship between inputs and outputs in a fuzzy system is characterized by a set of linguistic statements which are called fuzzy rules. The number of rules in a fuzzy system is related to the number of fuzzy sets for each input variable. In this work 2 input variables having respectively 5 fuzzy sets were used leading to a theoretical number of 25 rules, as shown in Table 1. However, it seemed reasonable to avoid 4 rules considering some limitations on the combinations of input variables which were impossible due to physical properties of the machining process. As an example, from the acquired experience, it was retained impossible to have at the same time very high tool wear and very small thrust force. In this way only 21 fuzzy rules have been used in this study to define POD. Since the conditions on thrust force and on drill wear state must be verified at the same time, each rule can be expressed as follows:

If thrust force is … AND drill wear state is …

THEN delamination is … .

Diagnosis process of POD, shown in fig. , can be easily explained by the following example.

Discrete values of the input variables (thrust force T_0 and drill wear W_0) are fuzzified by the relative membership functions: both of them belong to two fuzzy sets with μ >0.

Then, based on rules matrix, combinations of T and W result in 4 rules for POD= very small and other 4 rules for POD=small. Through the use of fuzzy min-max algorithm, i.e. fuzzy intersection (AND) and fuzzy union (OR), the following inference equation can be generated to calculate the fuzzy membership values for POD:

$$\mu(POD)_{D_i} = \bigcup_{j=1}^{k} \{\mu(T) \cap \mu(W)\} \qquad (3)$$

where $\mu(POD)_{Di}$ ($i=1,2,\ldots,5$) is the fuzzy membership value for delamination with D_1=very small, D_2=small etc., and $j=1,\ldots,k$ represents the number of rules fired for the corresponding POD. Once determined the outputs of the inference process are still fuzzy values and need to be defuzzified. The commonly used centroid defuzzification produces the centre of area of the union between D_1 and D_2.

5.3 Fuzzy control for feed rate

The crisp value of POD then obtained can be used as an input to the fuzzy logic controller which generates the feed rate to optimally control the drilling machine. The correlation between feed and POD is also governed by fuzzy rules. When the occurrence of delamination is high less feed rate has to be used. Table 2 shows the five rules which were designed to control feed rate based on the results from diagnosis on POD.

Finally the non-fuzzy value obtained after the inference process can be use for a real time control of feed to drive the CNC machine tool with the least possibility of composite damage while maintaining the maximum use of drill life.

		1	2	3	4	5
IF	POD is	VS	S	M	H	VH
THEN	*f* is	VS	S	M	H	VH

Table 2: Fuzzy rules for feed rate.

6 CONCLUSIONS

In this paper several experiments have been performed with a twofold purpose of investigating the severe drill wear and the delamination damage in the drilling process of CFRPs by conventional tools.

It has been shown how tool wear was mainly affected by cutting speed and drilled length within the range examined. Tool wear increased significantly as cutting speed increased. This represented the major constraint

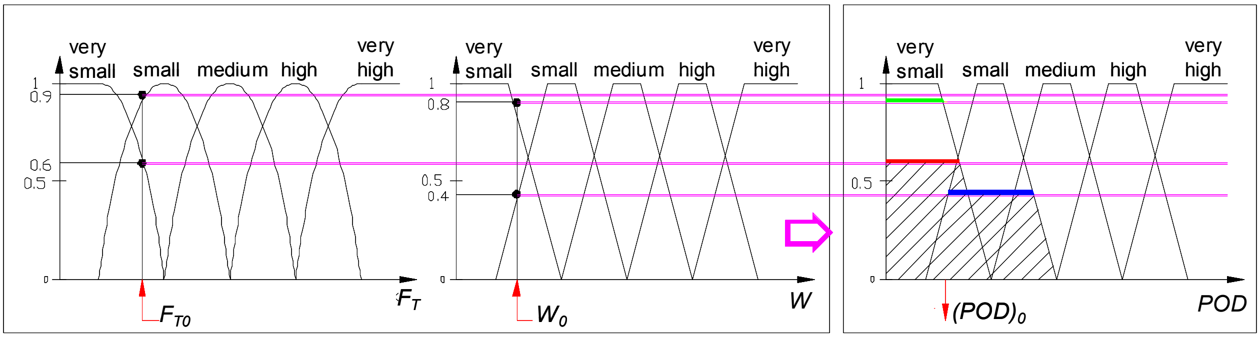

Figure 6: Fuzzy diagnosis of POD.

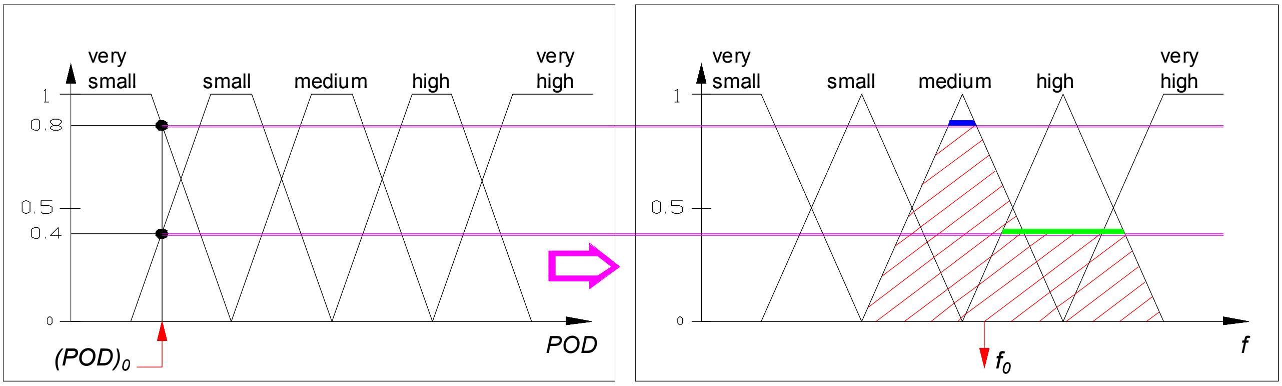

Figure 7: Fuzzy logic control for feed rate.

for using HSS tools to drill carbon fiber reinforced plastics at high speeds. Although tools worn out quickly and the thrust force increased drastically with cutting speed, an acceptable hole entry and exit quality was anyway maintained. This was because fiber interlacements of the fabric warp acted as a crack stopper to avoid the propagation of the delaminated area. Further studies should afford the effective residual strength of the laminate after the drilling process enabling detailed investigations of the internal surface and especially of the mechanical properties.

A theoretical approach for a fuzzy logic controller was also presented in this paper providing a feasible study for on line monitoring of cutting conditions (in terms of thrust force and drill wear state) and damage on the composite material. A feedback control on feed rate was proposed to improve performance of worn tools without increasing push out delamination. However, there are limits in this kind of application since it is heavily dependent on the amount of experimental work allowing to establish a sufficient set of rules which are the key-point for the implementation of fuzzy logic control.

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