ENHANCING THE MACHINING PERFORMANCE OF HSS DRILL IN THE DRILLING OF GFRP COMPOSITE BY REDUCING TOOL WEAR THROUGH WEAR MECHANISM MAPPING

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ABSTRACT

The wear characteristics of cutting tools is affected by the machining factors such as the magnitude of the cutting speed, extent of the cutting tool movements in the feed direction, the geometry of the cutting tool etc. This research paper presents some original research into the wear types, as well as the phenomena that occurs in the cutting tool/work material interface zone and their relationships to cause different wear mechanisms (adhesion, abrasion and diffusion) in hole machining process. A wear mechanism map involving the tool wear characteristics of uncoated High Speed Steel (HSS) drill of 6mm diameter is constructed for the drilling of Glass Fiber Reinforced Polyester (GFRP) composite laminates. Different wear modes observed and identified by the surface micrograph image of land / flank of uncoated HSS drillsto describe a number of wear mechanisms. The dominant wear mechanisms include adhesive wear, adhesive and abrasive wear, abrasive wear and fatigue / thermal wear. In the wear mechanism map, a wear region was identified, which is called "safety cutting zone" or "mild wear zone", where the minimum flank wear of the HSS drill tool occurs. In order to carry out the drilling operation on the GFRP composite in the "safety cutting zone" or "mild wear zone", it was found that the spindle speed should be set in the range of 1200-1590 rpm and feed rate must be set to 0.10 – 0.16 mm/rev. Thus, the wear mechanism map constructed here can be used as a reference for selecting suitable drilling parameters of uncoated HSS drill tools for GFRP composites.

Key words: GFRP composites, drilling, wear mechanism map, wear mechanism, HSS drill, safety cutting zone

1. INTRODUCTION

Machining using the cutting tool is the collective process of friction and wear at the tool work interface zone. During machining, the cutting tool undergoes tool wear that reduces the life of the cutting tool, reduces the productivity but increases the surface roughness of the machined work pieces. In recent days, Polymer Matrix Composites have found wide range of applications starting from household appliances up to the extent of automobile and aircraft components. Drilling is one of the most essential machining operation used for polymer matrix composites in assembly operation using fasteners [1-3]. Because of the discovery of more effective and efficient automobile/aircraft components and their corresponding materials, along the addition of modern CNC machines for machining, the manufacturer's prerequisite is to increase the life of cutting tools during the machining process in order to increase the machining efficiency and to lower the manufacturing/production cost. However, the study on the wear rates and wear mechanisms of cutting tools in drilling of polymer matrix composites are very limited and are still not enough to meet the industrial requirements of manufacturing and machining [2]. Therefore the wear rate map and wear transition / mechanism map pertaining to a specific cutting tool / work piece pair becomes prominent for selecting the appropriate machining parameters since the whole wear rate map and wear mechanism maps areplotted under various machining process conditions and machining parameters.

In later 80's, Lim and Ashby constructed the first wear mechanism map in the tribology field [4,5], which combined theoretical and practical works together. In the early 90's, a wear mechanism map of aluminum alloys was constructed by Liu [6,7]. After systematic studies on the wear process of cutting tools, Lim, Liu and coworkers constructed few wear maps of tools cutting steels, which used feed rates and cutting speeds as two axis respectively [8,9,10]. These maps explained the tribological characteristics of

HSS tool while machining steels and relative wear mechanisms in different regions under dry running conditions.

Drilling is an important machining of the polymer composite material, so the wear mechanism map of drilled tools was studied in this paper. Also, in this research, the wear mechanism map of uncoated HSS tools during dry-drilling of the polymer composite material is constructed, and the safety zone is identified in which the wear rate of tools would be minimum [15]. It is also possible to use the wear mechanism maps for other form of machining, to predict the general trend of tool wear, such as the approximate location of the lower-wear regions [11].

These maps will also be treated as good references for choosing suitable processing parameters for uncoated HSS tools drilling of GFRP composites. These maps describe the tribological features of HSS tool drilling GFRP composite and relative wear mechanisms in different regions under dry machining conditions [15]. In this research the wear mechanism map of uncoated HSS tools drilling GFRP composite laminates is constructed by considering drilling process parameters at different levels. The work piece material (GFRP composite laminate of thickness 10mm), tool material (uncoated HSS drill), tool diameter (6 mm) are fixed under dry drilling machining condition. The drilling operation is carried out on the CNC vertical machining center, and thus the data collected to construct the wear map are more reliable. In the end, the wear map for HSS tools drilling GFRP composite will be related to practical machining conditions to optimize machining parameters. These maps can become a good reference for choosing process parameters of uncoated HSS drills in the machining of GFRP composites.

2. MATERIALS AND METHODS

2.1. GFRP Material Fabrication

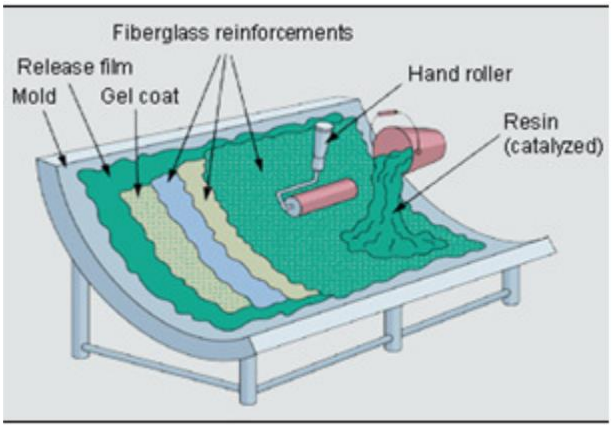

Figure 1 Schematic of hand lay-up technique

Figure 2 Schematic of hand lay-up technique

Table 1 GFRP composite specifications

Matrix Material	Isophthalic Polyester resin
Fiber	S-glass fiber
Fiber diameter	15 microns
Fabric type	Stitched mat type
Fiber orientation	Random
Fiber weight fraction	33%
Material density	1.6 g/mm^3
Laminate thickness	10 mm

The GFRP composite laminate was fabricated to a fiber weight fraction of 33% by mixing approximately 2 kilogram of Isophthalic polyester resin with 1 kg of randomly oriented structural glass reinforcement and the hardener (Poly Ether Ether Ketone). Laminate sample with dimension of 600×600×10 mm was fabricated using hand lay-up process (Figure 1). The laminate was hardened under atmospheric temperature and pressure conditions for a period of 24 hours. The properties of the GFRP composite are listed in Table 1. The GFRP composite laminate after the fabrication and atmospheric curing is shown in Figure 2.

Table 2 Drill Tool dimension specifications

Tool Material	High Speed Steel
Tool diameter	8 mm
No. of Flutes	2
Point angle	118°
Helix angle	30°
Flute length	77 mm
Shank type	Cylindrical

The wear mechanism / transition map of uncoated HSS drills of 8mm diameter, machining GFRP composite laminates is constructed through the wear data collection. The wear data is collected through experimental work, carried out by considering drilling process parameters at different levels. The GFRP laminate is manufactured for a constant thickness of 10mm and is used for machining operation. Bosch manufactured uncoated HSS drills of 6 mm diameter (refer Table 2 for specifications) was used for drilling in dry run condition.

In order to maintain accuracy and data reliability, the drilling operation on the GFRP composite was carried out on Computer Numerical Controlled (CNC) Vertical Machining Center (VMC) (Figure 3). During machining, 80 holes of 6 mm diameter were drilled on the GFRP composite laminate using uncoated HSS twist drill (Figure 4). The drilled holes are spaced on the composite laminate as per the drill hole specifications and standards for fasteners. The spindle speed varied from 1200 rpm(cutting speed = 22.62 m/min) to 1800 rpm (cutting speed = 33.93 m/min) while the feed rate is varied from 0.1 mm/rev to 0.3 mm/rev as shown in Table 3. Each experimental run was designed with different parameters by applying the Design of Experiments (DoE) concept as shown in Table 1.

Figure 3 VMC performing drilling on composite laminate

Figure 4 HSS drills of diameter 6, 8 and 10mm

Before and after drilling the holes, the HSS drills were cleaned with Acetone and NaOH solution to remove the impurities. A fresh HSS drill was used for each experimental run and two replications of each run was carried out and the average of the resultant was computed for wear data collection. In the present research, the tool wear rate was measured by applying the weight difference method. A digital weighing machine with an accuracy of 0.0001g was used for the weighing purpose. The average of, weight difference of two replication of each experimental run is calculated and considered for analysis and for plotting wear rate maps. The wear data along with the study of micrograph images are used for plotting the wear maps. To get a dimensionless wear rate value, the value of the wear rate measured was normalized [12,13].

The drill cutting speed and feed rate were employed as abscissa and ordinate during wear rate and wear mechanism map plotting. The wear maps were plotted by normalizing wear data on a log scale so as to get the dimensionless wear rate. The following equations [14] were used for this purpose.

Normalised wear rate = $W_n = W/A_n$; where W= wear rate and A_n = Nominal contact area

W = wear rate = Mass lost in time / Density ($mm^3 min^{-1}$)

Mass loss = $Mass_{before} - Mass_{after}$ / Time (g/min)

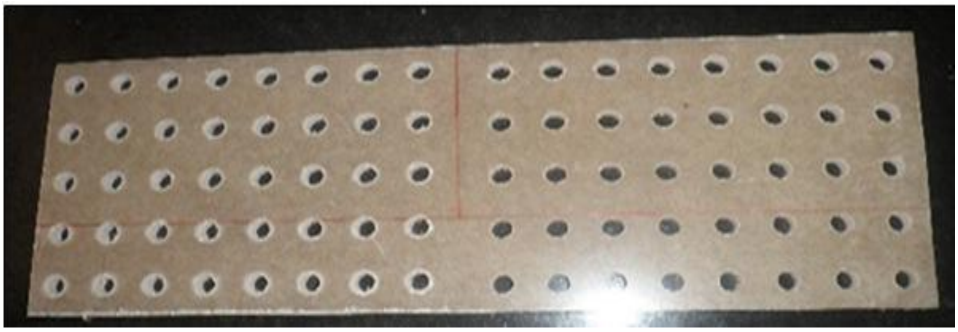

Figure 5 GFRP laminate with 80 holes drilled

After drilling 80 holes on the GFRP composite laminate, as shown in Figure 5.1, the drills were placed under the focus of Inverted Trinacular metallurgical microscope (Figure 5.2) to capture the micrograph images with a magnification factor of 500X to study and plot different wear mechanisms.

Figure 6 Trinocular Inverted Metallurgical microscope

Figure 6 show the Inverted Trinacular Metallurgical Microscope for surface morphology analysis. The drills were accurately held in a fixture in a proper position while capturing the images of the drill land and chisel edge areas. The captured images were interfaced and stored in the computer with the help of ENVISION software.

2.2. Wear Rate Map for 6 mm diameter HSS Twist drill Machining GFRP Composite

The drilling process factor and their level values undertaken for the wear mechanism map of 6mm HSS twist drill while machining GFRP composite laminate was displayed in Table 3. The normalized wear rate calculations were done as per the equations mentioned in the previous section.

Table 3 Normalised wear rate data of 6mm HSS drill

Cutting speed (m/min)	Drill feed (mm/rev)	Mass difference, M_d(gms)	Machining time, M_t (min)	Mass lost in time, M_l (gms/min)	Wear rate, W_r, mm^3/min	Normalised wear rate, W_n	Log (norm. wear rate)
22.62024	0.1	0.003	6	0.0005	0.057670127	3.6207E-05	-4.4412
24.50526	0.1	0.0026	5.53846154	0.00046944	0.054145841	3.3995E-05	-4.46859
26.39028	0.1	0.0025	5.14285714	0.00048611	0.056068179	3.5201E-05	-4.45344
28.2753	0.1	0.0024	4.8	0.0005	0.057670127	3.6207E-05	-4.4412
30.16032	0.1	0.0025	4.5	0.00055556	0.064077919	4.023E-05	-4.39545

32.04534	0.1	0.0027	4.23529412	0.0006375	0.073529412	4.6164E-05	-4.33569
33.93036	0.1	0.003	4	0.00075	0.08650519	5.4311E-05	-4.26511
22.62024	0.15	0.0022	4	0.00055	0.06343714	3.9828E-05	-4.39981
24.50526	0.15	0.002	3.69230769	0.00051458	0.059352172	3.7263E-05	-4.42872
26.39028	0.15	0.0018	3.42857143	0.000525	0.060553633	3.8018E-05	-4.42002
28.2753	0.15	0.0018	3.2	0.0005625	0.064878893	4.0733E-05	-4.39005
30.16032	0.15	0.0019	3	0.0006	0.069204152	4.3449E-05	-4.36202
32.04534	0.15	0.0021	2.82352941	0.0006375	0.073529412	4.6164E-05	-4.33569
33.93036	0.15	0.0024	2.66666667	0.000675	0.077854671	4.888E-05	-4.31087
22.62024	0.2	0.0019	3	0.0006	0.069204152	4.3449E-05	-4.36202
24.50526	0.2	0.0017	2.76923077	0.00065	0.074971165	4.7069E-05	-4.32726
26.39028	0.2	0.0015	2.57142857	0.0007	0.080738178	5.069E-05	-4.29508
28.2753	0.2	0.0015	2.4	0.00075	0.08650519	5.4311E-05	-4.26511
30.16032	0.2	0.0015	2.25	0.0008	0.092272203	5.7932E-05	-4.23708
32.04534	0.2	0.0018	2.11764706	0.00085	0.098039216	6.1552E-05	-4.21076
33.93036	0.2	0.0021	2	0.0009	0.103806228	6.5173E-05	-4.18593
22.62024	0.25	0.0018	2.4	0.00075	0.08650519	5.4311E-05	-4.26511
24.50526	0.25	0.0015	2.21538462	0.0008125	0.093713956	5.8837E-05	-4.23035
26.39028	0.25	0.0014	2.05714286	0.000875	0.100922722	6.3363E-05	-4.19817
28.2753	0.25	0.0014	1.92	0.0009375	0.108131488	6.7889E-05	-4.1682
30.16032	0.25	0.0015	1.8	0.001	0.115340254	7.2414E-05	-4.14017
32.04534	0.25	0.0017	1.69411765	0.0010625	0.12254902	7.694E-05	-4.11385
33.93036	0.25	0.002	1.6	0.001125	0.129757785	8.1466E-05	-4.08902
22.62024	0.3	0.002	2	0.0009	0.103806228	6.5173E-05	-4.18593
24.50526	0.3	0.0017	1.84615385	0.000975	0.112456747	7.0604E-05	-4.15117
26.39028	0.3	0.0016	1.71428571	0.00105	0.121107266	7.6035E-05	-4.11899
28.2753	0.3	0.0015	1.6	0.001125	0.129757785	8.1466E-05	-4.08902
30.16032	0.3	0.0016	1.5	0.0012	0.138408304	8.6897E-05	-4.06099
32.04534	0.3	0.0019	1.41176471	0.001275	0.147058824	9.2328E-05	-4.03466
33.93036	0.3	0.0022	1.33333333	0.00135	0.155709343	9.7759E-05	-4.00984

3. METHODOLOGY OF WEAR MAPPING

The following steps are involved in the construction of wear rate / mechanism maps in the present research work.

- For the pair of materials considered in this research work i.e., Glass Fiber Reinforced Polymer (GFRP) composite and HSS drill bits, their contact mode (unidirectional through hole drilling), their contact geometry (surface contact), the working environment condition in which the pair of materials are to interact (CNC drilling) and lubrication condition (dry run) is decided before starting the experiment.
- Experimental wear data was gathered from the in-house drilling experiments carried out on the CNC-Vertical Machining Center. Mathematical models describing wear behavior of this pair should be gathered through the literature review.
- The process parameters to be used as the two axes of the wear map and also their range to be included on the wear maps is decided.
- According to the mode and mechanism of wear, the wear data are grouped. The wear-rate / wear transition / wear-mechanism data, appropriately classified, are then plotted on the two-dimensional axes defining the map. Each mechanism is then separated using boundaries and the approximate locations of the contours of constant wear rate. At this stage, the wear map is sufficiently informative showing different wear mechanisms on the wear rate map.

- The final step is to identify the "safety zone" or "safe working region" "low wear zone" where the overall / total drill tool wear is going to be minimum. This zone gives the optimum range of process parameters that could minimize the tool wear, indirectly enhancing the operational performance, tool life of the drill tool and ending with increased productivity

For the present research work, the spindle speed and the feed rate were chosen as two axes required for constructing the two dimensional wear map of HSS tools drilling GFRP composites. The wear rate maps were drawn by normalizing the wear rate values against spindle speed and feed rate. Wear maps were built by taking cutting speed (rpm)as abscissa, and the feed rate (mm/rev) as the ordinate.

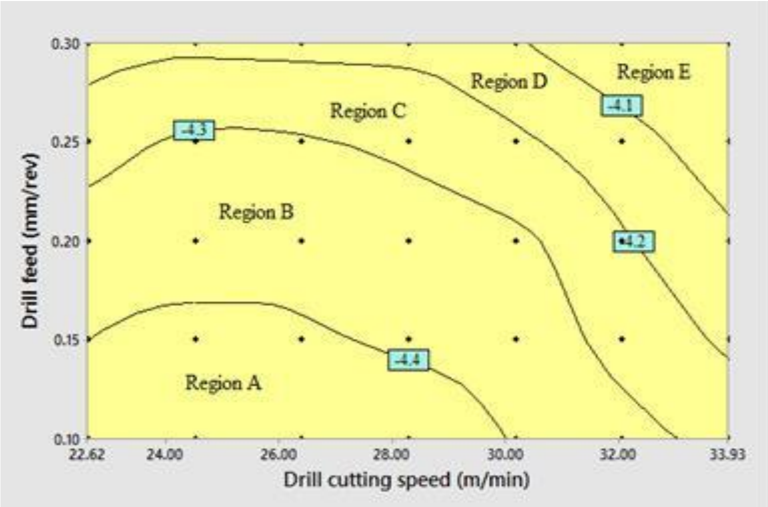

Figure 7 Wear rate map of 6mm HSS drill machining GFRP composites

Figure 7 shows the wear rate map of uncoated HSS tool of 6mm drill under dry machining of GFRP composite laminates. The wear rate map was plotted by taking the drill cutting speed as abscissa and the drill feed rate as ordinate. Different regions on the wear map were identified and demarcated where similar wear rates were obtained. For the present wear map study, five such regions were identified and were automatically demarcated using MINITAB software. The range of wear rate for each region was set as: - 4.4 and below (Region A), -4.4 to -4.3 (Region B), -4.3 to -4.2 (Region C), -4.2 to -4.1(Region D) and - 4.1and above (Region E). Rigorous examination of worn surfaces of the drill in different regions on the
wear rate map was done to identify the HSS drill wear mechanisms. The micrograph observations of the worn surfaces of drill land, chisel edge and flank area were taken with a magnification factor 500X for the microanalysis. The wear mechanisms were decided after examining a number of micrograph images with respect to each of the region and by considering the best among them.

3.1. Results and Discussion on Micrograph Analysis (drill diameter=6mm)

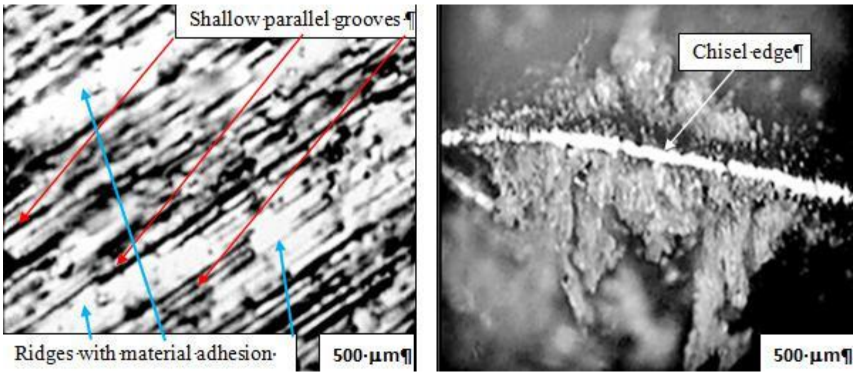

Figure 8 Composite adhering on to the 6mm HSS drill land and chisel edge

The micrograph images of the worn land surface of the drill for a feed rate of 0.15 mm/rev and cutting speed of 26.39 m/min(spindle speed=1400 rpm) is shown in Figure 8.The micrograph image in this Region A displayed the adhering of composite material on the drill land surface (left side image of Figure 8) and the chisel edge of the drill (right side image of Figure 8). A machined surface with shallow parallel grooves (red arrows) and uneven spreading of matrix material (polyester) transfer around the ridges on the land was observed (blue arrows). The micrograph image findings implied that, under this machining condition, the drill wear was governed by adhesion of work material on the drill land, which showed the presence of adhesive wear mechanism in region A.

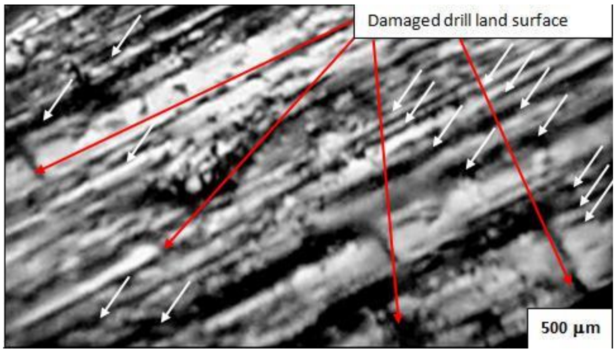

Figure 9 Worn land surface of the 6mm HSS drill under a feed rate of 0.2 mm/rev and at a cutting speed of 28.27m/min

Figure 9,shows the micrograph image of the worn drill land surface under Region B at a feed rate of 0.2 mm/rev and cutting speed of 28.27m/min (spindle speed=1500 rpm). The micrograph image displayed more transferred matrix metal and distribution of white lumps of matrix material over the surface area of the drill land. The red arrows in Figure 9 indicated the locations of the damaged and abraded ridges on the drill land surface. This is usually seen on those cutting tools suffering from abrasive wear mechanism (Zhang, 2001). So, a similar finding was observed here, with the GFRP composite material adhered on the ridges of the drill land. Along with this, the abraded and damaged parallel ridges (white arrows in Figure 9) confirmed a combination of adhesion and abrasion wear mechanism in region B.

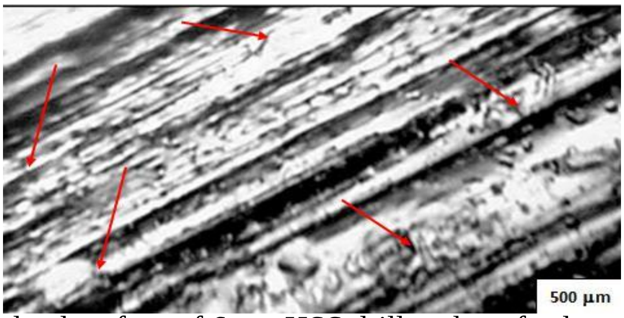

Figure 10 Worn land surface of 6mm HSS drill under a feed rate of 0.2 mm/rev & at a cutting speed of 30.16 m/min

The micrograph of the worn surface of the drill land under a feed rate of 0.25 mm/rev and a cutting speed of 30.16 m/min (spindle speed=1600 rpm) is observed in Figure 10. This machiningcondition was with respect to region C. The micrograph observations revealed parallel and deeper plowing grooves. Small cuts and damages were also observed on the edges of the grooves which are shown by the arrows in Figure 10. The random orientation of the fibers will cause uneven abrading of the surface they come across during machining. Thus the rough and uneven land surface demonstrated more abrasion i.e., more wear rate, compared to regions A and B. The more wear rate could also be due to the hardness and abrasive nature of the debonded glass fibers (especially silicon carbide present in glass). All these actions were reflected in the above micrograph image which confirmed more abrasion of the drill land surface and inferred that the abrasive wear is the major wear mechanism in region C.

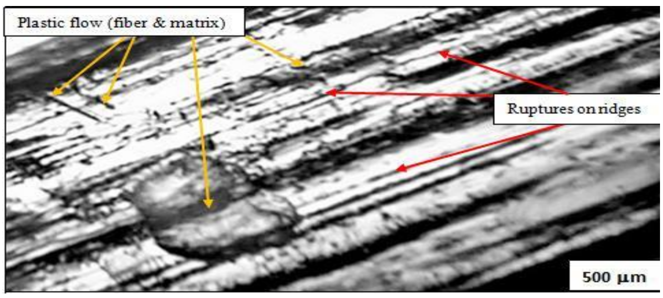

Figure 11 Worn land surface of 6mm HSS drill under a feed rate of 0.25 mm/rev & at a cutting speed of 32.04 m/min

Figure 11, shows the micrograph of the worn surface of cutting tool under a feed rate of 0.25 mm/min and a cutting speed of 32.04 m/min (spindle speed=1700 rev/min). At these high machining conditions (corresponding to Region D), the image revealed the presence of plastic flow of the matrix and fiber (shown by yellow arrows). The ruptured ridges, long and shallow cracks were also observed on the worn surface (red arrows). Thus the wear in region D could be due to the matrix melting and depositing at the tool work interface during machining. Therefore drilling in region D should be avoided to overcome the drill damage.

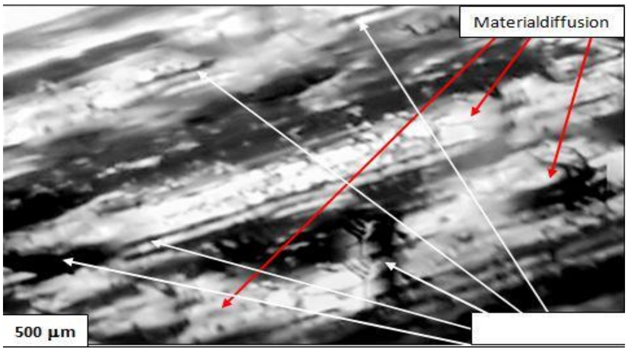

Figure 12 Worn land surface of 6mm HSS drill under a feed rate of 0.30 mm/rev and at a cutting speed of 34 m/min

Figure12 shows the micrograph image of the worn surface of cutting tools under a feed rate of 0.3 mm/rev and a cutting speed of 34 m/min (spindle speed=1800 rev/min). More material transfer, diffusion were detected which could be due to the more frictional and thermal impact at the tool-work interface because of the increased level of machining factors. The worn surface in region E was also observed with small cracks. The land surface was composed of smooth waves and smudges of transferred material from the work piece. Figure 12 also showed small eroded slots.

3.2. Wear Mechanism Map for 6mm HSS Drill Machining GFRP Composite

Based on this and the above micrograph observations, the wear mechanism map for 6 mm HSS drill during dry drilling of GFRP composite was developed and is shown in Figure 13. The wear mechanisms observed by the microscope images included adhesive wear, adhesive and abrasive wear, abrasive wear, plastic flow and thermal / fatigue wear. Closer examination ofthese mechanisms suggested that the plastic deformation controlled regimes/ zones included: the zone A, B and C with different wear rates of -4.4 to -4.2. Thus, the wear mechanisms under plastic deformation regions could be adhesive wear, adhesive and abrasive wear, and abrasive wear. From the micrographs also it could be seen that the major damage to the drill land occurred due to adhesion and abrasion. As shown in Figure 8 and other micrograph images, adherent work piece material progressively grew during the drilling process and the Silicon carbide present in the glass fibers were responsible for the abrading action on the surfaces of the drill. The thick layers of material were the indication of layering or overlapping. These were the indications of the extensive plastic deformation and shearing action experienced during drilling. The small cuts and the small scratch marks showed in micrograph (Figure 10) suggested that are markable amount of abrasion and plastic deformation took place during drilling. All these indications showed that the major wear mechanisms under the low machining conditions could be adhesion and abrasion wear mechanisms and to support this, these two mechanisms covered major area under the plastic deformation. Grooves of varying sizes were commonly observed throughout the examined worn surfaces. The formation of such grooves during the drilling of composites has links to the process of fiber debonding. The small cracks running on the drill land surface indicated the severe abrasion of the surface due to the rubbing action of the SiC particles as well as the debonded fibers from the matrix during machining (Figure 11). The micrograph findings also indicated that the regimes D and E were thermally sensitive and were temperature controlled regions with the wear rates of -4.2 to -4.1 and above -4.1. The micrograph analysis also indicated that the wear mechanisms in these regimes could be plastic flow / fatigue wear and machining in these regimes must be avoided.

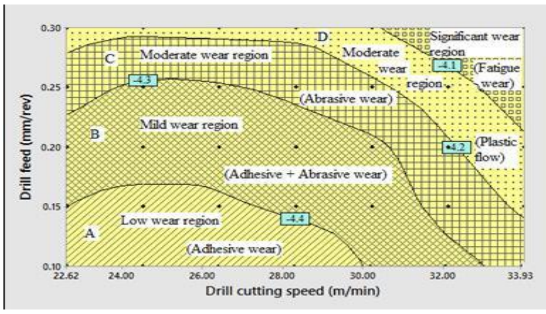

Figure 13 Wear mechanism/transition map of 6mm HSS twist drill machining GFRP composites

Another important feature of the wear rate map was the presence of a "Safety region" or "Low-wear region" where the tool wear rate was observed to be the lowest. This indirectly informed that the wear rate of HSS drill during machining could be minimized by maintaining the levels of the process parameters within the safety zone boundary of the map, which might improve the tool performance and cutting tool life. In Figure 7, Region A had the lowest wear rate ranging from −4.4 and below, which could be named as "Safety zone", for 6mm HSS drill machining GFRP composites. It was inferred that the life of the drill could be enhanced if the drilling parameters were made to operate within the range, of the "Safety zone" (Zhang, 2001, Wang, 2008). Thus, from Figure 13, for 6mm HSS drill, the process parameters corresponding to the "Safety zone / Low wear zone" were found to be:

Drill cutting speed: 22.62 m/min – 30 m/min (drill spindle speed = 1200 – 1590 rpm)

Drill feed rate: 0.10 – 0.17 mm/rev

These machining factors could enhance the drill life for specified work material, tool material and machining combinations.

4. CONCLUSION

- The wear rate maps were clearly delineated into Low wear region, Mild wear region, Moderate wear region, Marginal wear region and Significant wear region. The regions in the diagram are delineated where similar wear-rates were obtained and the boundaries are plotted according to the observed change in the wear rate.
- Micrograph observations showed adhesive pits, voids, adhesion of polyester matrix, minor cracks, deep parallel ridges and plowing marks on the land / flank surface of the HSS drill.
- Five types of wear mechanisms were identified in the present work based on the micrograph observations of the worn surfaces of uncoated HSS tools, during the drilling of GFRP composites.
- The main wear mechanisms in the map include built up edge, adhesive wear, adhesive and abrasive wear, abrasive wear, plastic flow and fatigue/thermal wear.
- In order to improve the operational performance of the drill tool for the specified GFRP material, tool material and machining conditions, the process parameters can be set corresponding to "safety cutting zone" or "mild wear region" so as to have minimum tool wear. The drill parameters that can be set for this are:

Drill cutting speed: 22.62 m/min – 30 m/min (drill spindle speed = 1200 – 1590 rpm)

Drill feed rate: 0.10 – 0.17 mm/rev

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