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Drilling of carbon epoxy composite using nanocrystalline nickel alloy coated tools

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Abstract

This paper is concerned with the effect of auto-catalytically deposited Nickel alloy coating on the machining performance of High Speed Steel (HSS) drill bits in the drilling of carbon composite. The present work is focussed on the performance comparison of nanocrystalline Nickel-Boron (Ni-B) coated and uncoated HSS twist drill bits of size 5 & 6 mm by evaluating tool wear, hole deviation error, extent of delamination, surface roughness of the hole when drilling carbon epoxy laminate. In addition to this the coating was also characterized by ICP-OES (Inductively Coupled Plasma), FESEM (Field Emission Scanning Electron Microscope), DSC (Differential Scanning Calorimetry) and NHT (Nanohardness Test) to study the composition, surface morphology, phase transformation behavior and nanohardness respectively. The coating showed typical nodular morphology in as-deposited condition. The activation energy required for the Ni-B coating to convert from meta-stable phase to stable crystalline phase was found out to be 160.4 kJ/mol. The coating showed the surface hardness of $1118HV_{30mN}$ and $1445HV_{30mN}$ in as-deposited and heat-treated conditions.

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1.0 INTRODUCTION

Composites especially carbon composites are being employed at a greater extent in aerospace and automotive industries due to its advantageous properties like low weight, high specific strength, stiffness and fatigue strength [1]. Carbon fibre is commonly used to reduce the weight of the structural components on aircraft and thereby improving fuel economy, reducing emissions and increasing carrying load [2].

Although composite components are produced to the required shape, machining is often needed to fulfil the requirements related to tolerances of assembly needs. Among all machining processes, drilling is the most indispensable method for the fabrication of products with composite panels [3]. The performance of these products is mainly dependant on surface quality and dimensional accuracy of the drilled hole. The material anisotropy resulting from fibre reinforcement considerably influences the quality of the drilled hole [4]. Hence, precise machining needs to be performed to ensure the dimensional stability and interface quality. The quality of the drilled hole depends on the thrust force and torque generated during drilling, which in turn is affected by the factors such as tool geometry, speed, feed rate etc [5].

The main troubles faced throughout the drilling of composite materials are delamination and fiber pull out [6, 7]. One of the major difficulties that persist while drilling is the consequence of access cutting temperatures on the quality of the drilled hole. Surfeit cutting temperatures have an effect on the dimensional accuracy of the drilled hole and worsen its surface finish. Excess cutting temperatures during drilling can melt the matrix and burn the drilled hole [8]. Research and experiments conducted on drilling of composite materials have revealed that as the cutting edges of the drill bit wear out, the heat generated and the thrust force produced increases. Increase in thrust force gives rise to delamination [6]. Amongst the variables to be measured for tool selection take account of the thickness of material, diameter of hole, tolerance necessities, hole-finish requirements and the composite material being drilled. Moreover tool geometry plays a big role in producing a hole with an adequate quality. In arid drilling the tool has to resist extreme environments, which consist of high temperatures, high frictional forces and huge mechanical loads. This requires the tool to possess high hot hardness, high refractivity and low coefficients of friction [9, 10].

Therefore, it is imperative to systematically scrutinize the performance of drill bit in terms of producing a good quality hole. In the present investigation a hard, uniform and wear resistant nanocrystalline Nickel-Boron (Ni-B) coating has been developed over the HSS twist drill bit of diameters 5 and 6 mm using electroless plating method for drilling carbon epoxy laminate. The Ni-B coating was characterized using ICP-OES (Inductively Coupled Plasma-Optical Emission Spectroscopy), DSC (Differential Scanning Calorimetry), FESEM (Field Emission Scanning Electron Microscope) and NHT (Nanohardness Test) to study the composition, crystallization temperature, surface morphology and nanohardness respectively. The performance evaluation of both coated as well as uncoated HSS drill bits were compared in terms of tool wear, extent of delamination, hole deviation error and hole surface finish after drilling 100 holes on carbon epoxy laminate.

2. EXPERIMENTAL

2.1 Sample Preparation

Coatings were made on mild steel and stainless steel samples specifically to analyze their composition and morphology and phase transformation respectively. Initially samples were polished with various grades of emery papers followed by final alumina polishing. Degreased samples were then cathodically cleaned and acid etched with intermittent rinse in deionized water. Then these samples were transferred to the electroless Ni-B plating bath for the required duration. The details of chemical composition of the plating bath and its operating conditions are given in Table 1. The deposition rate obtained was about 6- 7 μm/hour.

Table 1: The chemical composition of the Ni-B plating bath and its operating conditions.

Chemical Composition	Concentration (g/L)
Nickel Chloride	15-20
Tri-sodium Citrate	30-40
Ammonium Shulphate	25-35
Lactic Acid	1-5 ml/L
Di-methyl amine borane	1-4
Operating Conditions	
pH	8±0.1
Temperature (°C)	90 ± 2

2.2 Coating Characterization

Elemental compositions of the electroless Ni-B deposit were determined using ICP-OES. The surface morphology of electroless Ni-B coating was examined using FESEM (Model Carl Zeiss). The phase transformation behavior of the coating was also done using Diamond DSC (Perkin Elmer Model) at different constant heating rates of 10, 20, 30 and 40 °C/min. Nanohardness measurements were made on both as-plated and heat treated deposits using a Nano Hardness Tester (CSM Make) and using Berkovich diamond indenter by employing a load of 30 mN.

2.3 Equipment for drilling experiments and drill evaluation

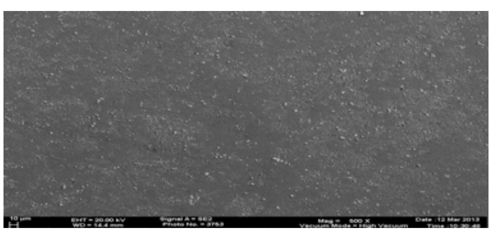
In order to study the effect of Ni-B coating on tool life, coated and uncoated HSS drill bits were tested and hole finish was observed. All the drill bits were tested by measuring tool wear and hole quality after drilling 100 holes on carbon epoxy laminate. Tool wear was measured in terms of flank and chisel edge wear using Toolmakers Microscope. The hole quality was checked by measuring the extent of delamination occurred after 101st hole using the "Echotherm" Pulse Thermography system. A long-wave cooled infrared camera (FLIR SC 3000) was used for the inspection. The specimen was thermally excited by a pair of Xenon flash lamps, the excitation power being 12.8 kJ for duration of 5 milliseconds. The series of thermal images acquired over a pre-determined period were analysed for variations in thermal contrast with respect to time. Further image processing was carried out using the 1st derivative option to clearly highlight the zones of damage around the hole. Surface roughness of the drilled holes was also quantified using Nano Map 3D Surface Profilometer. In an automated system, the drilling process itself needs to be controlled and ideally optimized. Existing practices typically decide on the feeds and speeds used taking into consideration the drill bit used, thickness and the material of the workpiece. For the drilling of metal, it is common to use the spindle speed advised by the tool designer, while the feed is found in tables according to the workpiece material and diameter of the hole. But in case of drilling composites, whatever be the material and diameter of the hole, it is always recommended to have low feed rate and high spindle speed. For the present study, the spindle speed of 2560 RPM and feed rate of 0.06 mm/rev were chosen. Drilling experiments were carried out in a Ravi Oerlikon semi-automatic vertical drilling machine. Plywood was used as a back/base support for the composite while drilling. A continuous air blower was provided with the drilling machine so as to remove the dusty chip formed at the end of drilling a hole.

3. RESULTS AND DISCUSSIONS

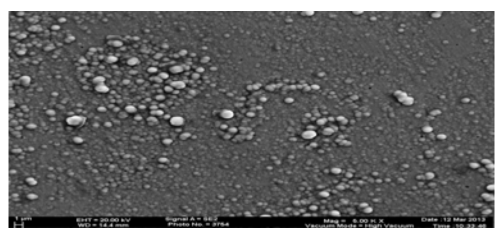
3.1 Composition. Morphology and phase transformation behavior of the coatings

The average composition obtained from ICP-OES analysis for the as-plated electroless Ni-B coating was 98.80 wt.% Nickel and 1.20 wt.% Boron.

The as-deposited electroless Ni-B coating exhibited nodular morphology when subjected to FESEM analysis as shown in Figure 1. It has been reported that the surface topography for the electroless Ni-B deposits was strongly dependent on the characteristics of electroless plating solution [11].



(a)



(b)

Fig. 1: Morphology of the as deposited Ni-B coating at (a) 500X (b) 5000X respectively.

To find out the phase transformation behaviour of the electroless Ni-B coating DSC studies were carried out at different scanning/heating rates of 10, 20, 30 and 40°C/min in the temperature range of 55-550°C. In general, the presence of exothermic peaks in DSC thermograph indicates the transformation of nanocrystalline/amorphous deposit to stable crystalline phases. Thermograph obtained at 40°C/min scanning rate for the deposit showed two exothermic peaks, one at 216.5°C and the other peak at 318.74°C. The low temperature peak present in the coating could be attributed to the structural relaxation such as annihilation of point defects and dislocation within the grains and grain boundary zones. The major exothermic peak in the DSC curve obtained for Ni-B coating corresponds to the long range atomic movements causing precipitation of the stable crystalline phases such as Ni and Ni_3B.

3.2 Nano Hardness Test (NHT)

Nanohardness measurements were made on the as-plated as well as heat treated (400°C for 1h) electroless Ni-B coated round samples. Table 2 shows the hardness value for Ni-B coating in as-plated and heat treated condition. From the table it is evident that the heat-treated Ni-B coating exhibited approximately 30% higher nanohardness value compared to as-deposited coating. The higher nanohardness value for heat treated sample could be due to the synergistic effect of formation of crystalline nickel and hard nickel boride precipitates.

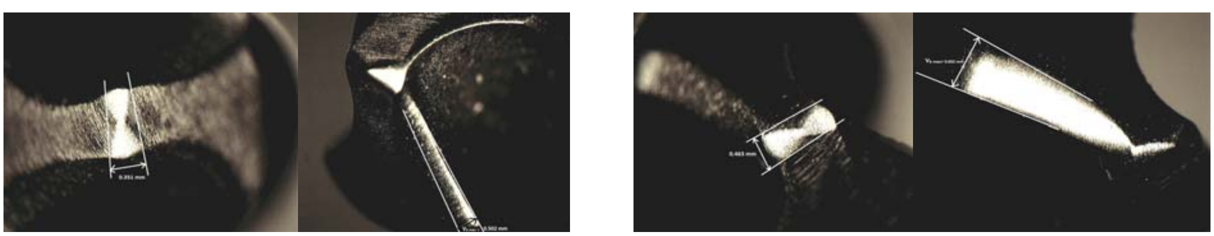
Table 2: Nano hardness of electroless Ni-B deposit in as-plated and heat-treated condition at RT & 400°C.

Temperature (°C)	Ni-B Nano Hardness (HV_{30mN})*
As-Plated {Room Temperature (RT)}	1118
Heat Treated (400)	1445

*** Average of five measurements**

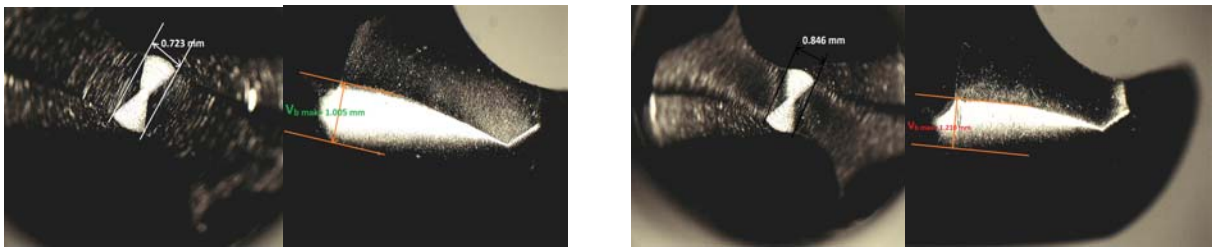
3.3 Tool Wear

The material removal characteristic was analyzed by considering tool wear in different stock removals. The wear of twist drills occurred on major flank, minor flank and on chisel edge. Figures 2 & 3 show the typical tool wear pattern of flank and chisel edges in uncoated and coated drill bits. From the Fig. 2 (a & b) it can be seen that the amount of chisel wear and flank wear in case of 5 mm Ni-B coated HSS drill bits were found to be approximately 25% and 16% lesser compared to the uncoated drill bits after drilling 100 holes respectively. Similar results were also obtained for 6 mm HSS coated and uncoated drill bits. The reason for this observation may be due to the improved mechanical properties of the coating provided on the drill bits such as high hardness, high thermal stability and low coefficient of friction.



(a) **(b)**

Fig. 2: Typical tool wear pattern for (a) Ni-B coated HSS 5 mm drill bit (b) uncoated HSS 5 mm drill bit, after drilling 100 holes in carbon epoxy laminate.



(a) **(b)**

Fig. 3: Typical tool wear pattern for (a) Ni-B coated HSS 6 mm drill bit (b) uncoated HSS 6 mm drill bit, after drilling 100 holes in carbon epoxy laminate.

3.4 Hole Deviation Error

Co-ordinate measuring machine was employed to measure dimensional and geometric deviations (hole diameter and roundness, respectively). Hole diameters were analyzed at 1st and 100th hole after drilling carbon epoxy laminate. Table 3 shows the variation in the hole diameter with respect to number of holes in case of coated and uncoated drill bits. From the table, it can be seen that, there is about 1% decrease in hole diameter and approximately less than 0.4% decrease in hole diameter after drilling 100 holes using the uncoated and coated HSS drill bits respectively. The coated Ni-B drill bits were able to machine 100 holes without an appreciable reduction in hole diameter.

Table 3: Drilled hole deviation using coated and uncoated drill bits of size 5 & 6 mm respectively.

Type of coating	Drill Diameter (mm)	Hole diameter at 1st Hole (mm)	Hole diameter at 100th Hole (mm)
Uncoated HSS	5	5.00	4.97
	6	5.98	5.93
Ni-B Coated HSS	5	5.01	4.98
	6	6.01	5.99

3.5 Extent of delamination

Figure 4 (a & b) depict the thermographic images of the 101st hole drilled using coated and uncoated HSS drill bits of sizes 5 & 6 mm respectively.

(a) **(b)**

Fig. 4: Thermographic pattens of (a) 5mm diameter and (b) 6mm diameter drilled holes using uncoated and Ni—B coated HSS drill bit indicating the extent of delamination.

From the above figure, it can be concluded that, the extent of delamination of holes drilled using Ni-B coated HSS drill bit is less compared to holes drilled using uncoated drill bits. In Figure 4(a), the extent of delamination for 5 mm drilled hole is depicted by the black region around the hole. The maximum extent of delamination around the hole is approximately 2 mm for uncoated HSS drill bit and approximately less than 1 mm for Ni-B coated HSS drill bit. Whereas, Figure 4(b) shows the extent of delamination for 6 mm drilled hole shown by the green region around the hole where the maximum delamination area is approximately 1.5 mm for uncoated HSS drill bit and approximately less than 0.75mm for Ni-B coated drill bit.

3.6 Surface Roughness of the drilled hole

The average surface roughness values (Ra) for the 101st hole drilled with uncoated and Ni-B coated HSS drill bits of sizes 5 & 6 mm respectively was measured using Nano Map 3D profilometer. In case of 5 mm hole drilled using uncoated HSS drill bit (Ra= 0.46 μm), the average surface roughness value (Ra) was found to be approximately 28% more than the Ni-B coated HSS drill bit (Ra= 0.36 μm). Also, holes drilled using 6 mm drill bit showed that surface roughness values for holes corresponding to Ni-B coated HSS drill bit (Ra= 0.33 μm) is about 17% less compared to holes corresponding to the uncoated HSS drill bit (Ra= 0.39 μm).

4. CONCLUSIONS

This study discussed the method for investigating the performance of auto-catalytically deposited Ni-B binary alloy on HSS twist drill bits during drilling of carbon epoxy laminate. The Ni-B coating was also deposited on mild steel specimens for characterizations. Based on the results following conclusions were drawn:

- FESEM results revealed the nodular morphology for the Ni-B deposit.
- Around 1.20% of B incorporation was found when the bath contained about 1.5g/L of boron source (DMAB).
- Heat-treated Ni-B deposit exhibited higher nanohardness value compared to the as-deposited Ni-B coating due to the formation hard and stable nickel boride precipitates.

- Drilling tests performed on carbon epoxy laminate showed that binary Ni-B coated HSS twist drill bits performed much better in terms of tool wear and hole deviation error when compared to uncoated HSS drill bits.
- Extent of delamination determined by Thermographic Non-destructive Evaluation was lesser in holes drilled using Ni-B coated HSS drill bits when compared to holes drilled using uncoated.
- The surface roughness value for the 101^{st} hole drilled using Ni-B coated drill was also less compared to holes drilled using uncoated.

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