Characterization of microwave-drilled holes in kenaf-reinforced epoxy composites

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KEYWORDS

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Microwave Drilling,
Heat-Affected Zone,
Circularity.

ABSTRACT

In this work, kenaf-reinforced polymer composites were drilled using microwave drilling technique. Microwave drilling utilizes microwave radiation at 2.45 GHz, which is concentrated in a narrow region using a thin concentrator. The 2 mm diameter cylindrical graphite and stainless steel (SS) were chosen as tools (concentrators)having sharp conical tips. Produced holes were characterized for heat-affected zone, hole circularity, and diametral overcut. The SS concentrator-drilled holes recorded more heat-affected zone than those drilled using graphite concentrator with the values of 44.16 mm^2 and 33.20 mm^2, respectively. Circularity of holes drilled using graphite concentrator was 15.32% higher than the circularity of holes drilled using SS concentrator. Further, graphite-drilled holes recorded 1.001 mm of diametral overcut which was 59.83% lower than that in SS-drilled holes. Therefore, graphite is recommended as a concentrator when kenaf-reinforced epoxy composites are to be drilled using microwave drilling.

1. Introduction

Composites are being used excessively in almost every filed of industry these days. Their use in automobile sector, sports industry, aerospace sector, antennas, and many other areas is elevating day by day (Rampal et al., 2022; Soutis, 2005). To fabricate the composites, numbers of materials have been explored which can act as reinforcements and can yield desirable properties. Natural fibers are some of the materials which when reinforced in the matrix, constitute the composites having wide range of applications. Easy availability, bio degradability, low density, less health hazards, and fracture resistance ability encourage the use of natural fibers as reinforcements in composites (Karimah et al., 2021; Sanjay et al., 2015). Adequate amount of strength and modulus with cheaper sources of origin, made natural fibers a lucrative option as the reinforcements. Most commonly used natural fibers are hemp, jute, flax, kenaf, and sisal. Among natural fibers, kenaf can grow very fast under large range of environmental conditions. Kenaf fiber has high flexural and tensile strengths that make it desirable as a reinforcement in composites (Radzuan et al., 2019; Yousif et al., 2012). Therefore, present study considered the kenaf fiber as a reinforcement.

It is difficult to manufacture large sized kenaf-reinforced polymer composites (KRPCs) for industrial applications. It may require very expensive machine tools and may acquire large space. Therefore, it is desired to manufacture small sized composite parts and then to fasten them using nuts and bolts, rivets, and other fastening techniques (Khashaba et al., 2006). For fastening, the KRPCs are drilled using various drilling techniques. Conventionally drilling KRPCs induces sever interplay damages such as delamination, fiber pull-out, micro cracking, etc., owing to the high intensity generation of mechanical forces because of rigorous tool and workpiece contact (Bonnet et al., 2015; Durão et al., 2006; Zarif et al., 2013). These defects deteriorate good qualities of parental KRPC and affect the performance of drilled holes.

Non-traditional drilling techniques are employed to reduce the drilling induced damages to some extent. Various drilling techniques, namely laser drilling, abrasive water jet drilling, and others have been explored so far in the literature to produce holes in KRPCs (Malik et al., 2021;

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Tewari et al., 2021). Microwave drilling is a new technique which is not explored much in the literature to drill polymer composites. In this technique, plasma is generated at the tool-workpiece interface. The heat thus produced ablates the workpiece and generates the desired hole (Jerby & Dikhtyar, 2003) . Therefore, in the present work, KRPCs are drilled using microwave drilling technique. The produced holes are apprehended on the basis of heat-affected zone (HAZ), circularity, and diametral overcut.

2. Experimental Set-Up

2.1. Materials and method of drilling

Two layers of kenaf fibers in mat form were reinforced in epoxy matrix using hand layup technique. Thickness of the resultant composites was 5 mm. Microwave drilling was chosen as the method to produce holes in above said material. Experimental set-up basically consists of a domestic microwave oven (Model No.: MC2846BG, Make: LG), a beaker, fixture to hold and support the workpiece, a tool or concentrator, tool holder (pin vice), and a microwave transparent jig plate to guide the tool holder to the workpiece (Fig.1). The 2 mm diameter cylindrical graphite and stainless steel (SS) rods were selected as the tool materials having sharp pointed tips. The tool tips are subjected to high temperature during machining. Therefore, the tool material should possess good thermal stability (Kumar & Sharma, 2018). The chosen materials sustain their properties even at elevated temperatures. The tool was grasped by stainless steel tool holder which is often termed as a pin vice. Further, the tool (gripped in the pin vice) was held in contact with the surface of workpiece. Workpiece was placed over the Teflon made fixture that is transparent to microwaves.

A number of pilot experiments was conducted on kenaf/epoxy composites at various microwave powers such as 540 W, 720 W, and 900 W, and different machining times. The 720 W and 16 s were recorded as the optimum parametric conditions that resulted in comparatively good quality holes. Therefore, kenaf epoxy composites were further drilled at above said parameters using the SS and graphite concentrators. The quality attributes of holes corresponding to both the concentrators were evaluated and compared with one another. To ensure the repeatability of the results, the experiments were conducted thrice corresponding to a parametric condition.

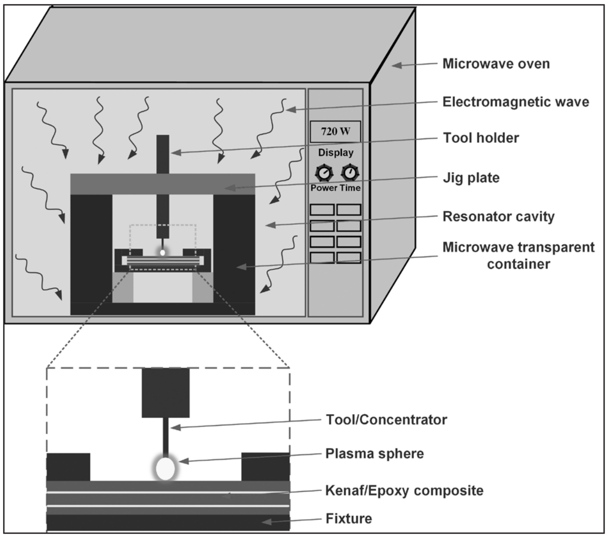

Fig. 1. Microwave drilling experimental set-up.

2.2. Material removal mechanism

Microwaves are electromagnetic waves where electrical and magnetic signals are perpendicular to each other. The material removal mechanism can be apprehended through seven stages (Fig.2) (Kumar & Sharma, n.d.; Lautre, 2015). In the first stage, electrical part of microwaves attracts the free electrons of concentrator to its surface. These free electrons are further accumulated at the sharp tip of concentrator (stage 2). Accumulation of electrons at the pointed tip causes high charge density which induces an electric field. Surrounding the electrode is the air, that acts as a dielectric medium. When the induced electric field exceeds the dielectric potential of surrounding air, then it ionises the air around the tip and causes the generation of plasma sphere (stage 3).

The high temperature plasma at the tip of concentrator interacts with the composite material in contact. It further raises the temperature of fibrous composite and removes the material after ablation (stage 4). The concentrator gradually advances into the workpiece owing to the dead weight of pin vice holding it, when the material is removed (stage 5 and 6). When the concentrator is pulled out of the specimen then a hole is created (stage 7).

2.3. Characterization of drilled holes

- Heat affected zone (HAZ)

The extent upto which the microstructure of the specimen is affected while drilling, is termed as the heat-affected zone. It consists of cracks,

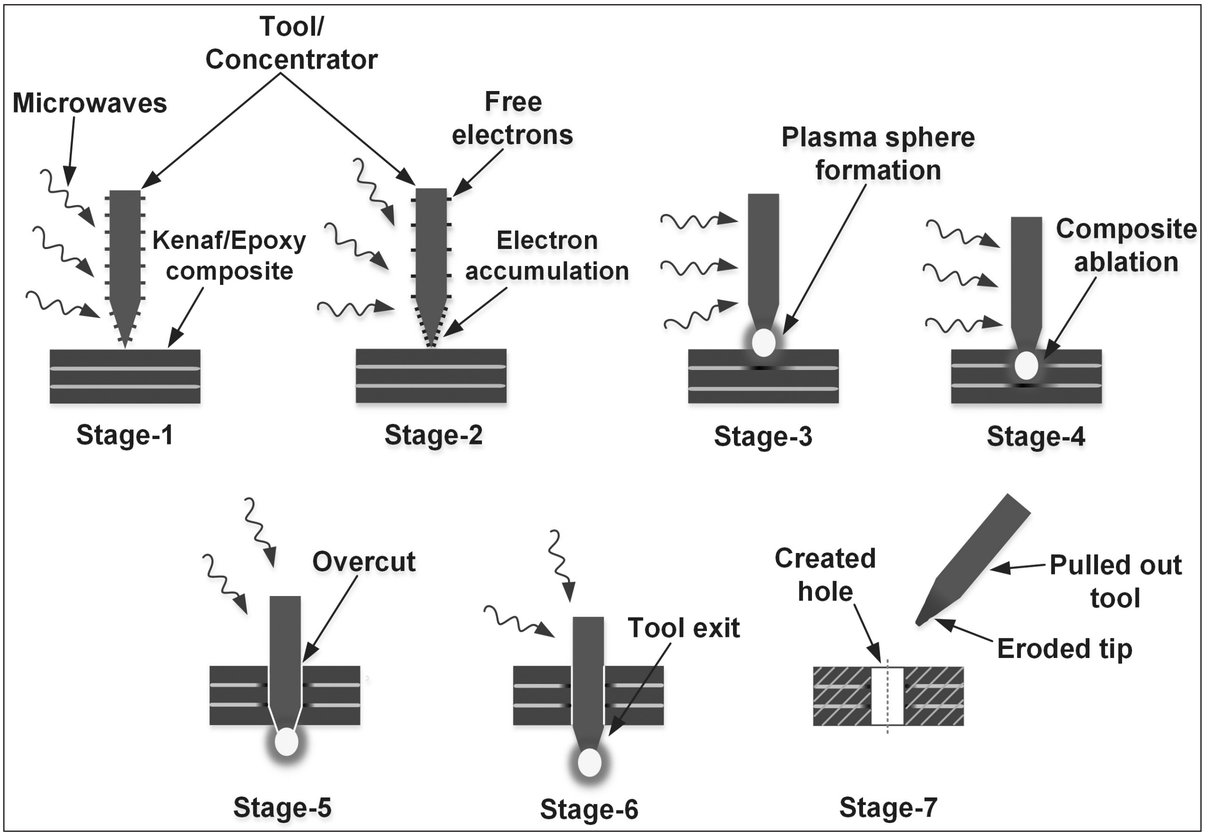

Fig. 2. Material removal mechanism in microwave drilling of kenaf/epoxy composites.

re-solidified layers and deposited carbon over the surface (Lautre et al., 2014; Tewari et al., 2021; Verma at al., 2020). The HAZ is measured as the difference between total area around the hole that consists of cracks, carbon deposits, and resolidified layers and area of the drilled hole.

- Circularity

It is the extent upto which circular holes are produced while drilling the specimens (Bharatish et al., 2013). In microwave drilling, the circularity depends upon various factors, namely tool diameter, tool material, microwave power, machining time, etc. Mathematically, circularity is defined as the ratio of minimum diameter to the maximum diameter of produced hole (Eq. 1).

$$Circularity = \frac{D_{min}}{D_{max}}$$

where, D_{min} is the minimum diameter, and D_{max} is the maximum diameter of produced hole (Singh & Sharma, 2020)

- Diametral overcut

It is the undesirable material loss around the concentrator throughout the hole thickness. Diametral over cut is the result of expanded plasma sphere around the tool periphery. Mathematically, it is represented as the difference of maximum hole diameter and diameter of the concentrator (Singh & Sharma, 2020).

3. Results and Discussions

3.1. Surface analysis of the concentrator

Figure 3 shows the SEM images of 2 mm diameter SS and graphite concentrators before and after the machining operation. Both the concentrators were having sharp pointed tips before producing holes. However, no pointed tip was sustained after the drilling operation. Graphite concentrator got blunt and the surface became uneven at the tip of it (Fig.3(b)). Concentrators were provided the gravity feed and therefore, the tip was in gentle contact with the workpiece. Owing to the high temperature plasma at the tool-workpiece interface, the properties of graphite are abated. It made the tool tip to get eroded and induced micro cracks on the surface. The SS concentrator was also affected owing to the high temperature plasma. Due to comparatively low melting point of SS, the material at the tip was melted and got accumulate (Fig. 3(d)).

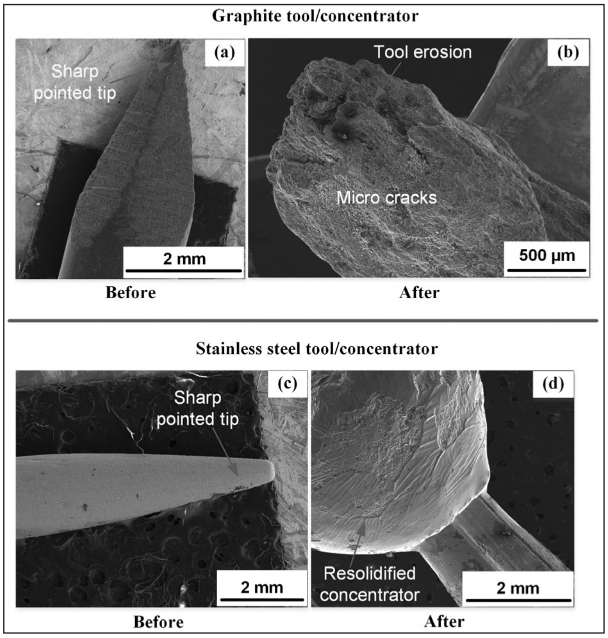

Fig. 3. SEM images of graphite concentrator; (a) before, (b) after the drilling operation, SEM images of stainless steel concentrator: (c) before, (d) after the drilling operation.

3.2. Heat-affected zone

Figure 4 (a and b) shows the HAZ in stainless steel and graphite concentrator drilled holes, respectively. The HAZ consisted of craters and epoxy ablation areas. These might be attributed to the interaction of high temperature plasma with epoxy which might have decomposed the epoxy and resulted in craters and ablated areas. During the ablation, a small quantity of gaseous products evolves from the epoxy at the temperature range of 200 °C to 500 °C (Neǐman et al., 1962).

Some material was also expunged along with SS concentrator while pulling it out (Fig. 4(a)). It was due to the resolidified SS accumulated at the tip of tool. Some unburnt fibers were also seen along the periphery of hole (Fig. 4(b)). The reason was the intermittent formation of plasma sphere. Moreover, the SS and graphite drilled holes recorded 44.16 mm^2 and 33.20 mm^2 HAZ, respectively. Graphite concentrator resulted in lesser HAZ around the hole and therefore, is recommended to drill kenaf/epoxy composites.

3.3. Circularity

Figure 5 (a and b) shows the SEM images at the entrance of holes drilled using SS and graphite concentrators, respectively. The minimum and maximum diameters of the drilled holes were marked and the circularity was evaluated using above said equation 1. In the results, graphite drilled holes recorded circularity of 0.760 which was 15.32% higher than that of SS drilled holes. Elevated tool wear and expunged material owing to the accumulated SS lowered the circularity in SS drilled holes. More circular holes are desirable and hence, graphite concentrator is preferred over the other to drill epoxy composites at above said process parameters.

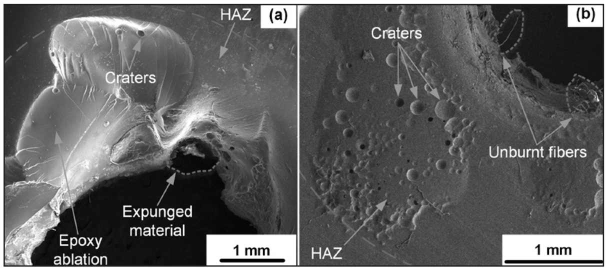

Fig. 4. Heat-affected zone at the entrance of holes drilled in kenaf/epoxy composites using, (a) stainless steel concentrator, (b) graphite concentrator.

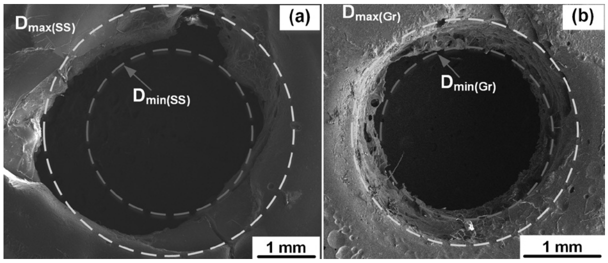

Fig. 5. SEM images at the entrance of holes drilled using, (a) stainless steel concentrator, (b) graphite concentrator with minimum and maximum diameters marked on them. [$D_{max(SS)}$ and $D_{min(SS)}$ - maximum and minimum diameters in stainless steel drilled holes, $D_{max(Gr)}$ and $D_{min(Gr)}$ - maximum and minimum diameters in graphite drilled holes].

3.4. Diametral overcut

Graphite drilled holes recorded 1.001 mm of diametral overcut which was 59.83% lower than that in SS drilled holes. Graphite concentrator sustained its cylindrical geometry even at elevated temperatures and resulted in less removal of material around the tool periphery (Kumar & Sharma, 2018). It was not the case with SS concentrator owing to its low melting point temperature. The tool eroded and undesirable accumulation of SS at the tip of concentrator resulted more diametral overcut around the drilled hole.

4. Conclusions

In this study, kenaf/epoxy composites were drilled using microwave drilling technique. The SS and graphite rods were considered as the concentrators as they provide good thermal stability. The following results can be concluded:

- The SS and graphite concentrators recorded 44.16 mm2 and 33.20 mm2 of HAZ around the drilled holes, respectively.
- Graphite concentrator resulted in the hole circularity of 0.760 which was 15.32% higher than that of SS drilled holes.
- Graphite drilled holes recorded 1.001 mm of diametral overcut which was 59.83% lower than that in SS drilled holes.

From the above discussions, it can be deduced that graphite drilled holes possessed better quality attributes when compared to that of stainless steel. Lesser HAZ, more circular holes, and lesser diametral overcut advocates the use of graphite concentrator to drill kenaf/epoxy composites.

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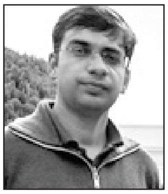

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