SIMULATION OF HEAT TRANSFER MODEL BASED ON FINITE ELEMENT METHOD FOR EDGE TRIMMING OF CFRP

Farrukh Hafeez[1], Jamal Sheikh-Ahmad [1], Fahad Almaskari[1] and Fanyu Meng[2]

[1] Department of Mechanical Engineering, Khalifa University of Science and Technology, Petroleum Institute, P.O. Box 2533, Abu Dhabi, United Arab Emirates

[2] Xi'an Jiaotong University, Xian Shi, Shaanxi Sheng, China
www.xjtu.edu.cn

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ABSTRACT

Carbon fiber reinforced composites are subjected to machining operations to obtain desired shape and dimensions. Edge trimming is one of the most commonly used post cure operation for the parts made from CFRP. Thermal loading of CFRP workpiece is inevitable during trimming process as some part of heat generated during the process dissipates into the workpiece. Accurate measurement and estimation of temperatures in the trimming zone is vital for understanding amount of heat evacuated through the workpiece. Finite element analysis is used to simulate the temperature field near and away from the trimming zone in this work. This computational model consists of two dimensional heat source representing the trimming tool cutting along the trimmed edge. The results from linear and uniform flux distribution are obtained and compared. The results are validated by measuring in situ temperature experimentally in the workpiece. Thermocouples are installed in the workpiece along perpendicular direction of the machined edge. Digital infrared thermography is used to measure temperature along the trimmed surface. Analytical methods are used to extrapolate the measurements to the point of interface. This model is an excellent tool to estimate heat partition into workpiece which has potential for extension and estimation of the part of the heat evacuated through the tool and chips.

1 INTRODUCTION

It can be assumed that the power consumed by the spindle is converted into the heat at the interface between the tool and workpiece during a machining operation [1]. This heat energy is dissipated to the CFRP workpiece, tool and carbon dust while trimming CFRP. The part of the heat dissipated into CFRP workpiece increases its temperature. Depending on the constituents of the CFRP, the material can undergo substantial thermal loading, thermal damage and delamination. Resin gets degraded in the cutting zone if the temperature exceeds glass transition temperature of the resin matrix [2]. Most of the fiber reinforced composites suffer from irreversible thermal damage above certain critical cutting speed [3] due to higher cutting temperatures. Thus, determination of heat partition, particularly, the part dissipating into the workpiece, is very important for the process optimization. Although substantial amount of studies on cutting temperatures in metal machining [4] are available, however relatively little literature is published on effect of temperature in machining of composites. For heat partition problems while machining metallic materials, researchers usually identified heat going into the workpiece by matching temperature data experimentally obtained with calculated temperature from analytical or computational models. However, this direct method has its limitation due high thermal gradients near tool-workpiece interface zone. A few authors attempted finite element modelling of CFRP machining [5,6] but these are limited to mechanical parameters excluding any consideration of thermal or temperature effects. Perhaps, full thermo mechanical modelling of machining is a complex process even for metal cutting as already reported in the literature [7]. Thus, it might require separate thermal modelling on its own for CFRP as a preliminary step prior to full thermo mechanical model. Alternatively, Inverse method is employed in measuring thermal parameters of the process. For example,

Corresponding author: Farrukh Hafeez, Department of Mechanical Engineering, Khalifa University of Science and Technology, Petroleum Institute, P.O. Box 2533, Abu Dhabi, United Arab Emirates.
fhafeez@pi.ac.ae, +97126075118

by measuring workpiece temperature comparing it to that obtained from a one dimensional moving heat source model [1]. Inverse method is rarely used for machining of composites and has not been reported for edge trimming as per author's knowledge. This technique is efficient and practical and proves useful to avoid problems due to steep thermal gradients at the contact zone when CFRP is subject to trimming operation. One way to validate this inverse method is to obtain temperature distribution into the workpiece which can be done with various techniques. Traditionally thermocouples have been used. More recently infrared thermography has been employed with availability of digital infrared cameras.

In this work, amount of the spindle power evacuating through the workpiece has been estimated. The temperature field has been simulated with finite element analysis model. The cutting motion of the burr tool along the trimmed edge has been assumed to be motion of a two dimensional heat source. The heat flux imparted to the workpiece has been calibrated by matching the simulated temperatures with the actual temperature of the workpiece measured with thermocouples. Thus part of the heat evacuated through the workpiece is measured through this inverse methodology.

THEORETICAL FORMULATION

The total heat flux generated in the contact zone is given as [1] (see figure 1)

$$q_t = \frac{P}{b \times a} \tag{1}$$

By the same principle, the part of the total heat flux directed to the workpiece is given as [1]

$$q_w = \frac{R_w \times P}{b \times a} \tag{2}$$

Where b is Trimming length
a is width of the panel
R_w is part of the power spent on the workpiece
P is power consumption by the trimming spindle
q_w is heat flux directed to the workpiece

The governing equation for this problem is the nonlinear transient three-dimensional system given as [8]

$$\frac{\partial}{\partial x}\left(k_{11}(T)\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{22}(T)\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{33}(T)\frac{\partial T}{\partial z}\right) = \rho c(T)\frac{\partial T}{\partial t} \tag{3}$$

Following is imposed as a boundary condition [8]

$-k_\eta(T)\frac{\partial T}{\partial \eta} = h(T - T_\infty)$ on top, bottom and machined surfaces,
$-k_{11}(T)\frac{\partial T}{\partial z}(0, y, z, t) = \dot{q}_w$ on the contact area between the cutting tool and the machined surface, where $\dot{q}_w$ is the amount of moving heat flux conducted into the workpiece,
$-k_\eta(T)\frac{\partial T}{\partial \eta} = 0$ on the remaining surfaces, and having the initial condition:
$T(x, y, z, t) = T_o$, at t = 0.

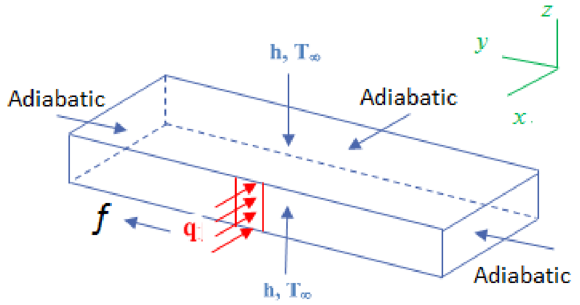

Figure 1: Schematic diagram of heat conduction state of CFRP workpiece subjected to Trimming. Heat flux *q*

Figure 2 :Trimming operation set up

NUMERICAL MODEL

Numerical model was constructed using Abaqus/Standard. Element type DC3D8 (thermal analysis), a 3D 8-noded linear brick (hexahedral) element, 88000 elements were used. Directional thermal conductivity $K_{11} = K_{22}$, K_{33}. DFLUX subroutine is employed at the trimmed edge to induce the moving heat source result from the contact between the cutting tool and the machined surface. Separate subroutines are developed for uniform and linear heat flux situations. Amount of heat flux was determined by minimizing the objective function [8]:

$$F = \sum_{p=1}^{r} \sum_{j=1}^{ns} \left(Y_{j,M+p-1} - T_{j,M+p-1}\right)^2 \tag{4}$$

where *Y* is measured temperature (°K) and *T* is simulation temperature (°K) at the boundaries. *j* is index of the thermocouple, *p* is the future time steps. *M* is general time index (*s*)

The workpiece dimension for computational model are length 250mm, width 30 mm and thickness 10 mm. Thickness is same as actual workpiece however length and width is reduced to reduce the computational effort, however such reduction does not affect the temperature prediction. Temperature gradient diminishes to room temperature beyond 30 mm as confirmed experimentally and analytically. Similarly a refined mesh is used in first 5 mm in direction of depth of cut and rest is a coarse mesh. It is assumed that material is orthotropic and effective thermal conductivity and specific heat properties are assumed throughout the workpiece. These properties are based on [9] and listed in table below.

Thermal Properties	Room Temperature	473 °K	Units
K_{11}	2.2	3.0	$J.s^{-1}.m^{-1}.K^{-1}$
K_{22}	2.2	3.0	$J.s^{-1}.m^{-1}.K^{-1}$
K_{33}	0.6	0.66	$J.s^{-1}.m^{-1}.K^{-1}$
c	820	1320	$J\ kg^{-1}\ K^{-1}$

Table 1: Thermal Conductivity and Specific heat of the workpiece

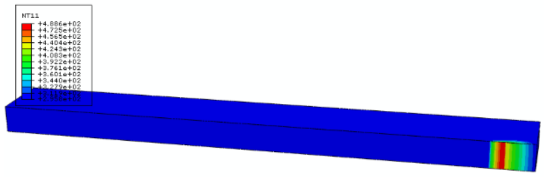

Figure 3: FEA model of two dimensional heat source moving along edge of the CFRP panel.

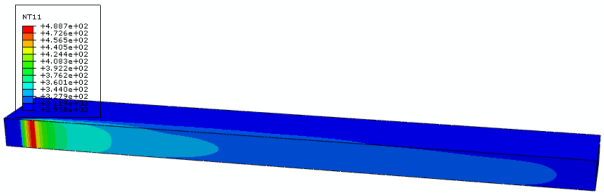

Figure 4: Top view of CFRP panel with temperature profile at bottom left due to the heat source near the end of trimming cycle.

Figure 5: Top view of CFRP panel with temperature profile at bottom right due to the heat source.

Figure 6: Top view of CFRP panel with temperature profile at bottom left due to the heat source near the end of trimming cycle.

EXPERIMENTAL SET UP:

An experimental rig has been assembled in order to measure insitu temperatures in the workpiece while CFRP workpiece is subjected to trimming operation. Figure 7 shows this rig which includes: (1) MultiCam Series 1000 CNC router equipped with 7.5kW, 24000 rpm spindle, (2) Fluke Ti400 infrared camera for capturing thermal images of the cutting area, (3) Load Controls UPC for measuring spindle power (4) a long CFRP panel (500mm long, 500mm wide, 10mm thick) is cut along its length with the (5) cutter at designated speeds and feed, which are 8000 rpm and 500 mm/min. Carbon dust or chips produced during the trimming operation are removed by vacuum suction around the cutting tool. Infrared thermography camera is placed such that the line of sight is at the level of workpiece cross section subjected to the trimming. It is relevant to mention that camera can capture temperature of the cutting edge accept the tool workpiece point of contact as tool is always in front of the camera. Five thermocouples are installed at the top surface of the workpiece directly aligned with the line of sight of the Infrared camera. These are type K thermocouples which are installed at known distance from the trimming edge. Fine blind holes with 1 mm depth are drilled and thermocouples laced with high conductivity paste are inserted into these holes so that the temperature gradient can be captured accurately. It is a tedious process requiring attention to the detail. Distance of the thermocouple nearest to the trimming edge has to be optimum such that the temperature could be measured at closest possible area of the tool workpiece interaction point as tool passes by it. Ideally it should be on the cross section but it is not possible physically as tool removes it along the material. Temperature gradient might diminish if it is installed too far from point of interaction. It is important to highlight that temperature gradient being too high near the cutting tool the data acquisition range has to be right to capture increase in temperature and then decrease as workpiece cools down. At the same time the vacuum suction system for carbon dust and chip collection can displace thermocouple thus require holding system in place. Distance of the thermocouples from the depth of cut is listed in table 2 below.

Thermocouple No	Distance from the Edge(mm)	Peak Temperature (°K)
Thermocouple 1	2.3	342.5
Thermocouple 2	4.74	317.06
Thermocouple 3	6.45	312.07
Thermocouple 4	8.2	308.75
Thermocouple 5	11.7	304.55

Table 2 : Thermocouple location and recorded Peak Temperature

These thermocouples are integrated with the lab view data acquisition system through NI9213 National instrument thermocouple input module installed in cDAQ-9174 four slot chassis. CNC router is programmed through its controller. Data acquisition system, infrared camera and machining operation are synchronized and initiated manually to capture data with clarity and consistency.

Figure 7: Experimental Setup for Edge Trimming

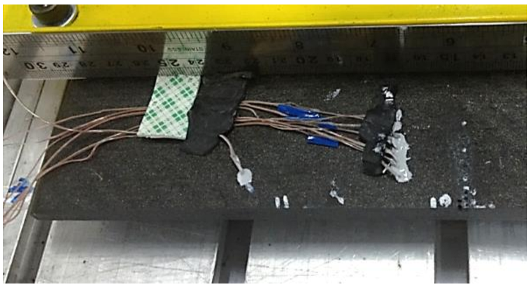

Figure 8: Set of thermocouples installed perpendicular to the machined edge

RESULTS AND DISCUSSION

The temperature measured with the help of thermocouples provide insight into the temperature profile as the edge is trimmed. These temperature values can be presented with the respect of time or distance from a given reference point e.g. distance from trimmed edge. These experimental results are comparable with the simulation results obtained from finite element analysis. One of the important parameter is the heat flux applied in the numerical model. It can be estimated based on spindle power consumption however accuracy is obtained by error minimization proposed in equation (4). The comparison of experimental and numerical results are shown in figure 9 figure 10 and figure 13. It is assumed that the heat flux is uniformly distributed along the machined surface.

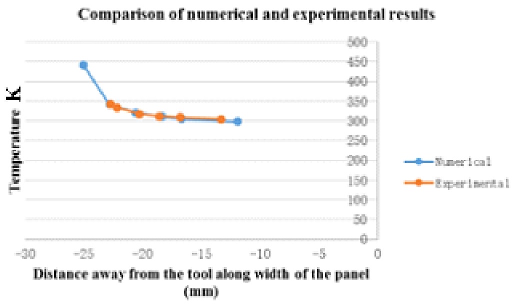

Figure 9: Comparison of temperature measured with a series of thermocouples perpendicular to the cutting edge and predicted by the model.

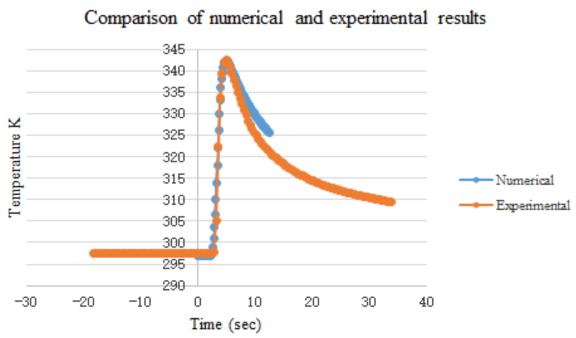

Figure 10: Comparison of temperature measured with a thermocouple nearest to the cutting edge and predicted by the model.

Figure 9 shows the peak temperatures captured by each thermocouple with respect to their respective distances from the cutting edge. Basically, it is the graphical presentation of the data in table 2. As expected, nearer the cutting edge the temperature is higher and it reduces as measured by thermocouples away from the cutting edge. Lowest temperature measurement made by furthest thermocouple No. 5 at approx. 11 mm distance is 31.4 °C. A distance beyond which temperature induced by heat flux does not propagate can be estimated based on data in table 2, for example through extrapolation of log values. For the current work, it is estimated that 30 mm away from the cutting edge it is safe to assume that part of the workpiece has room temperature. It is challenging to measure temperature experimentally any closer than the first thermocouple to the cutting edge. Here numerical simulation lends itself to estimate the temperature in this region and tool workpiece interface. Which is just under 450°C.

Figure 10 shows time history of the temperature observed by the thermocouple No. 1. This sensor records room temperature when the cutter is approaching but substantially away as can be seen on left had side of the graph. As the cutter approaches thermocouple the temperature rises steeply and peaks at approximately 342 °C. When cutter starts moving away from the sensor the temperature reduces smoothly back to the room temperature. The numerical model based on the uniformly distributed heat flux on the cutting surface is also shown as blue line. However the data presented is for smaller time period or duration as compared to the experimental data. Simply, because the length of the workpiece is half of the actual one to save the unnecessary computation time and effort. It exhibits room temperature and similar trend of shooting temperature steeply upwards as cutter approaches. It peaks similar temperature range with a difference of only few degrees Celsius. Then the temperature decay starts with time as the tool moves further away. The numerical simulation shows that temperature reduces slower as compared to the experimental results. This might be contributed by the inconsistency in material properties, particularly thermal conductivity. It is assumed that thermal conductivity for this orthotropic material is effective throughout the workpiece which may not be consistent in actual workpiece. Moreover the vacuum suction and air flow might cause temperature reduction quicker in the experiments.

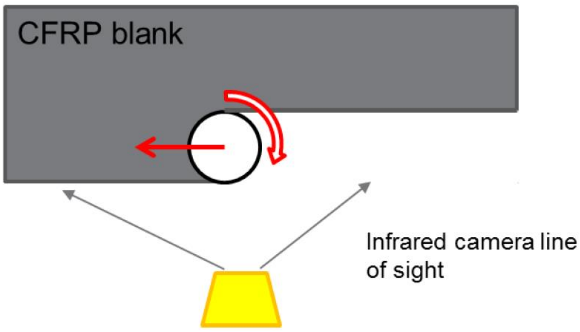

Figure 11:Schematic presentation of rotation and direction of the tool

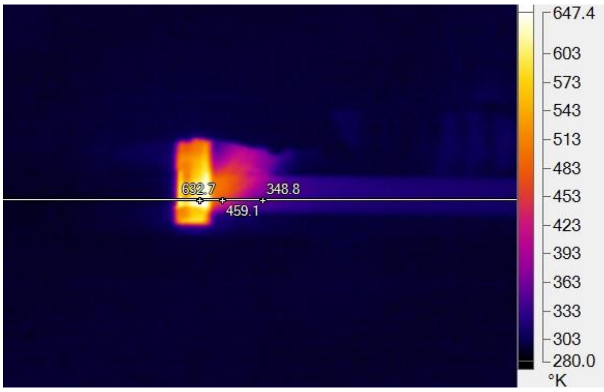

Figure 12: Thermography image of the cutting region showing tool temperature, dust temperature and machined edge temperature.

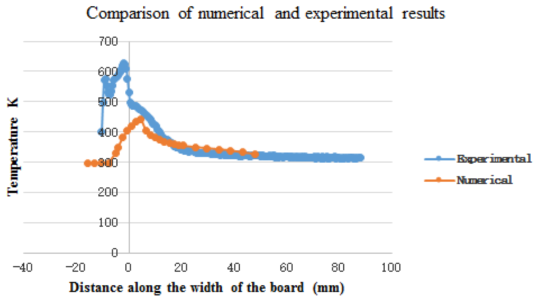

Figure 13: Corresponding temperature profile viewed as infrared thermography camera line of sight

Figure 11 shows schematic diagram for capturing radiometric image. Line of sight of the camera is shown in the figure. Note that view of the tool workpiece interface is obstructed by the tool location. Figure 12 shows the actual radiometric image. Temperature of the tool, workpiece and carbon dust sucked by vacuum is shown at respective cross hair position. The emissivity of the tool and workpiece is measured directly by comparing with black body of known emissivity for example black electrical tape. Emissivity values of the tool and workpiece are 0.83 and 0.85 respectively. It is assumed that emissivity of the carbon dust is same as that of the workpiece. Moreover the temperature profile along the machined cross section is obtained along with white line line on the machined cross section.

The temperature obtained from this image is plotted in figure 13 as a blue line. Region on the left of origin of x-axis represents temperature of the tool in the image. Temperature values just right to this origin represent dust temperature up till approximately 15 mm on x-axis. Rest of the data further to the right represents temperature of the trimmed edge. The temperature values obtained from the numerical modelling are compared with experimental results in figure 13. The orange line represents numerical results. There is good comparison in the numerical and experimental results for the temperatures on the trimmed edge. However it is substantially low as compared to rest of the experimental data particularly that of the tool temperature. It is due to the fact that the current numerical model does not include tool, thus only temperature of the workpiece is simulated. Where experimental data of tool temperature is shown the corresponding numerical results represent workpiece temperature.

It is assumed that the heat flux distributed by the tool on the cutting surface is uniform along the thickness. It is certainly simple to implement however may be an over simplification. Particularly if specific cutting energy is considered at tooth and away. Here linear distribution assumption can be closer to the actual cut. Hence linear distribution is assumed and DFLUX subroutine is developed to implement profile of the heat flux. The results obtained are compared with uniform distribution and experimental results in figure 14, figure 15 and figure 16. It is interesting to see that the difference in results from uniform and linear distribution assumption are not much different. Trend and profile is same but there is a slight shift in the results.

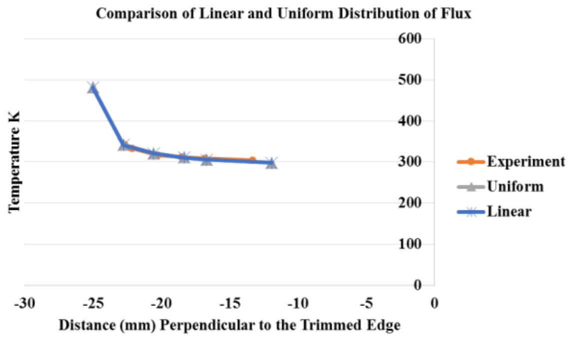

Figure 14: Results from the linear and uniform heat flux distribution compared with peak temperatures measured with thermocouples experimentally

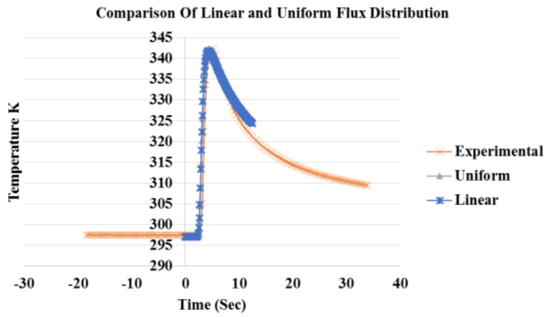

Figure 15: Results by assuming linear and uniform heat flux distribution on the trimmed surface. Comparison with temperature measured with thermocouple nearest to the machined surface

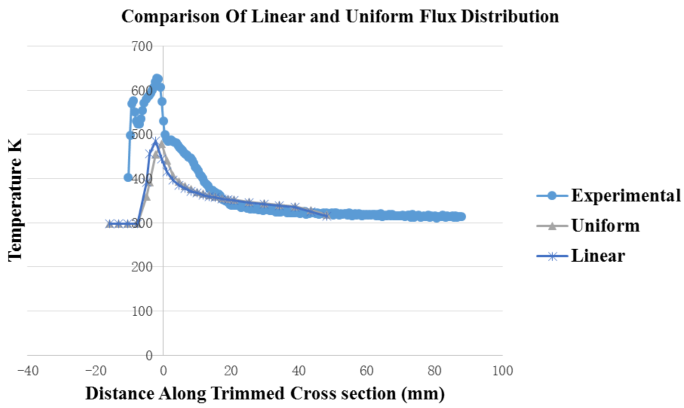

Figure 16: Temperature profile on the machined edge estimated by assuming linear and uniform heat flux distribution and compared with experimental data from thermography.

The total spindle power measured by the load cell is approximately 536 Watts. If it is assumed that total spindle power is converted into heat energy and amount of heat flux producing temperature fields is 500000 $J.s^{-1}.m^{-2}$ then by using equations (1) and (2) one can conclude that 4.66% of the heat is dissipated through the workpiece.

CONCLUSIONS:

In this article, finite element analysis is employed to simulate temperature fields near and away from the trimming zone. The trimming tool is assumed as two dimensional heat source. As that heat source moves along the cutting edge it imparts heat into the workpiece. Thus temperature field is obtained. These temperature fields are validated by experimental measurement of the temperature with the help of thermocouples. Excellent comparison is obtained between experimental and numerical results by estimating heat flux through error reduction. This heat flux is quantified as just under 5% of the overall spindle power evacuating through the workpiece. This inverse methodology has a potential of further development. It is can extended by developing model for the cutting tool and calculating part of heat dissipated through the tool and the carbon dust. Such work can be used for optimizing cutting parameters for quality output or minimum machining damage. A full scale thermo mechanical numerical model is an ideal outcome as a future work. Such work would simulate complete model including workpiece, tool, carbon dust and the trimming operation to derive relation between total energy consumed and dissipated into kinetic and heat format.

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REFERENCES

[1] E. García, D. Méresse, I. Pombo, S. Harmand, and J. A. Sánchez, "Identification of heat partition in grinding related to process parameters, using the inverse heat flux conduction model," *Appl. Therm. Eng.*, vol. 66, no. 1–2, pp. 122–130, 2014.

[2] H. Wang, J. Sun, J. Li, L. Lu, and N. Li, "Evaluation of cutting force and cutting temperature in milling carbon fiber-reinforced polymer composites," *Int. J. Adv. Manuf. Technol.*, vol. 82, no. 9–12, pp. 1517–1525, 2016.

[3] V. Schorník, M. Dana, and I. Zetková, "The influence of the cutting conditions on the machined surface quality when the CFRP is machined," *Energy Procedia*, vol. 100, no. C, pp. 1270–1276, 2015.

[4] N. A. Abukhshim, P. T. Mativenga, and M. A. Sheikh, "Heat generation and temperature prediction in metal cutting: A review and implications for high speed machining," *Int. J. Mach. Tools Manuf.*, vol. 46, no. 7–8, pp. 782–800, 2006.

[5] V. K. Doomra, K. Debnath, and I. Singh, "Drilling of metal matrix composites: Experimental and finite element analysis," *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 229, no. 5, pp. 886–890, 2014.

[6] D. Arola, M. B. Sultan, and M. Ramulu, "Finite Element Modeling of Edge Trimming Fiber Reinforced Plastics," *J. Manuf. Sci. Eng.*, vol. 124, no. 1, p. 32, 2002.

[7] B. Haddag and M. Nouari, "Tool wear and heat transfer analyses in dry machining based on multi-steps numerical modelling and experimental validation," *Wear*, vol. 302, no. 1–2, pp. 1158–1170, 2013.

[8] Brito, R.F., Carvalho, S.R.,Lima E Silva, S.M.M., "Experimental investigation of thermal aspects in a cutting tool using comsol and inverse problem" Applied Thermal Engineering vol. 86, pp. 60–68, 2015.

[9] R. Joven, R. Das, A. Ahmed, P. Roozbehja van, B. Minaie, "Thermal Properties of Carbon Fiber Epoxy Composites with Different Fabric Weaves," 2012, Proceedings of the SAMPE International Symposium, Oct 22-25, Charleston, SC.