A CUTTING FORCE MODEL IN TURNING OF GLASS FIBER REINFORCED POLYMER COMPOSITE

Ioannis NTZIANTZIAS*, John KECHAGIAS, Nikolaos FOUNTAS***, Stergios MAROPOULOS****, Nikolaos M. VAXEVANIDIS*****

* University of Thessaly, Greece
** TEI of Larissa, Greece
*** School of Pedagogical & Technological Education (ASPETE), Greece
**** TEI of Western Macedonia, Greece

In Memory of Prof. G.P. Petropoulos (1959-2010)

Abstract. The estimation of cutting forces in longitudinal turning of metals can be performed by applying the semi-empirical method developed by Kienzle and Victor, known also as specific cutting resistance model. Although this model is well documented for metals it has not been applied for new materials such as composites. The K_{st1}, and (1-z_t) constants of the Kienzle-Victor model for a glass fibre reinforced Polyamide (PA66 GF-30) are experimentally determined in the present work.

Keywords: Glass fibre reinforced polymer (GFRP), Turning, Cutting forces, P20 carbide tool, Kienzle - Victor model

1. Introduction

Fiber reinforced polymer composites constitute an important class of materials in advanced structural applications owing to their light weight, high stiffness and mechanical strength, and are nowadays in competition with metals. They are widely used for manufacture in diverse industrial fields: defense, automobile, space, aerospace and electronics industries [1].

Machining of glass fibre reinforced polymer (GFRP) composites has been reported in a number of publications by applying either experimental or numerical techniques [2-4].

The machinability of an engineering material denotes its adaptability to machining processes in view of factors such as cutting forces, tool wear and surface roughness [1]. Machinability is of utmost importance in industrial practice under nowadays very high quality product requirements; however, unlike common engineering metals and alloys, there is lack of data and empirical models for the machinability parameters in the machining of polymer composites [2, 4]. On the other hand, knowledge of the cutting forces developed in the various machining processes under given cutting factors is of great importance, being a dominating criterion of material's machinability, to both: the designer-manufacturer of machine tools, as well as to the user.

For the calculation of cutting forces in turning processes the empirical equation of Victor and Kienzle [5, 6] has been established as a common model, in particular for metals, on the basis of extensive experimental investigations [7]. On the contrary, applications of this model to polymers and composites are rather limited due to lack of appropriate data.

The purpose of the present work is to apply Kienzle-Victor analysis for the prediction of cutting forces in turning of a glass fibre reinforced polymer composite. The k_{st1}, and (1-z_t) constants of this model were determined by statistical techniques using experimental data from a research concerning cutting forces developed during turning of the GFRP composite Ertalon 66 GF-30® [2]. Predicted values are in good agreement with the measured ones.

2. Fundamental equations

The prediction of the cutting forces in longitudinal turning is based on the method proposed originally by Kienzle and Victor and considered nowadays as a common and reliable simple model [8]. This model assumes that there is a relationship between the theoretical chip thickness (t_o) and chip width (b) with the main cutting force (F_t) following the equation (1):

$$F_t = b\ k_{st1} t_o^{(1-z_t)} \tag{1}$$

Taking into account tool geometry and the cross section of the chip ($A = s \cdot a$), equation (1) can be rewritten as:

$$F_t = a k_{st1} s^{(1-z_t)} \quad (2)$$

In equation (2), a is the depth of cut (mm); s is the feed rate (mm per revolution); and k_{st1} is the specific cutting resistance (daN/mm^2) when theoretical chip cross section is 1 mm^2. The values of the constant k_{st1} and the exponent (1-z_t) for various materials, in particular metals, are given in handbooks and/or machinability databases. On the contrary, such data are not available, to the authors' knowledge, for advanced materials including FGRPs. For the prediction of the cutting forces, through equation (2), the k_{st1}, and (1-z_t) constants of Kienzle-Victor model were determined by statistical techniques from a series of experiments concerning turning of a GFRP composite [2].

3. Experimental

External longitudinal turning was performed in a Colchester 2500 lathe. The composite used for cutting is specified as ERTALON 66-GF30 (PA 66-GF 30). The test specimens were in the form of bars 150 mm in diameter and 500 mm in length. They were carefully clamped on the headstock and a tailstock was used, considering the reduced elasticity modulus of the polymer matrix [1]. The cutting tool material was P20 cemented carbide of the throwing insert type and of square form. The clearance angle was $\alpha = 5°$, the tip radius 0.8 mm and the rake angle $\gamma = +6^o$. Cutting depth kept constant during the experiments (2 mm). For the cutting forces measurements a Kistler three-axis piezoelectric dynamometer type 9257B was used. During machining, tool wear is maintained within the limit as per ISO specification and no cutting fluid was used. A two parameter experiment was designed using full factorial design (Table 1). Each experiment is repeated three times and the average of the measured cutting forces was used.

Table 1. Cutting parameters and experimental values of the cutting force F_t

s (mm/rev)	v (m/min)	F_t (N)
0.05	200	33.12
0.1	200	60.24
0.16	200	95.56
0.2	200	115.08
0.26	200	142.89
0.05	350	30.24
0.1	350	57.78
0.16	350	87.78
0.2	350	104.61
0.26	350	135.93
0.05	500	29.11
0.1	500	53.07
0.16	500	82.79
0.2	500	99.84
0.26	500	127.82

4. Results

Through equation (2), k_{st1} and z_t will be initially correlated with the feed rate s for each value of speed v, separately. The following Tables 2-4 present calculated values in logarithm form.

Table 2. Log(F_t/a) and Log(s) for cutting speed 200m/min; a = 2 mm

s (mm/rev)	F_t/a (daN/mm)	Log(s)	Log(F_t/a)
0.05	1.656	-1.301	0.219
0.1	3.012	-1.000	0.479
0.16	4.778	-0.796	0.679
0.2	5.754	-0.699	0.760
0.26	7.395	-0.585	0.869

Table 3. Log(F_t/a) and Log(s) for cutting speed 350 m/min; a = 2 mm

s (mm/rev)	F_t/a (daN/mm)	Log(s)	Log(F_t/a)
0.05	1.512	-1.301	0.180
0.1	2.889	-1.000	0.461
0.16	4.389	-0.796	0.642
0.2	5.231	-0.699	0.719
0.26	6.797	-0.585	0.832

Table 4. Log(F_t/a) and Log(s) for cutting speed 500m/min; a = 2 mm.

s (mm/rev)	F_t/a (daN/mm)	Log(s)	Log(F_t/a)
0.05	1.456	-1.301	0.163
0.1	2.654	-1.000	0.424
0.16	4.140	-0.796	0.617
0.2	4.992	-0.699	0.698
0.26	6.391	-0.585	0.806

Based on the values from Tables 2-4, plots presented in Figures 1-3 were constructed. From the above diagrams and taking into account the linear correlation of Log(F_t/a) to Log(s), for each value of cutting speed and the fact that the correlation coefficient R^2 is quite high, the extracted values of Log(k_{st1}) and (1-z_t) are summarized in Table 5.

Table 5. Log (k_{st1}) and (1-z_t) for each value of cutting speed

v (m/min)	Log(k_{st1})	(1-z_t)
200	1.398	0.91
350	1.358	0.904
500	1.328	0.898

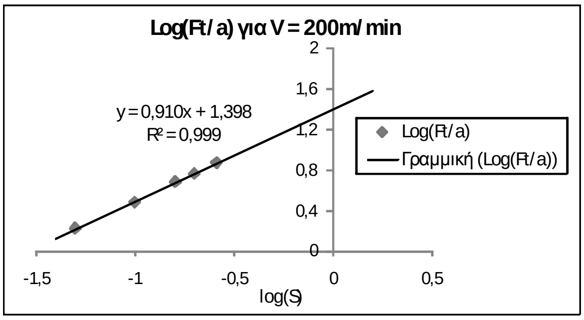

Figure 1. Linear correlation between Log(F_t/a) to Log(s) for cutting speed 200 m/min

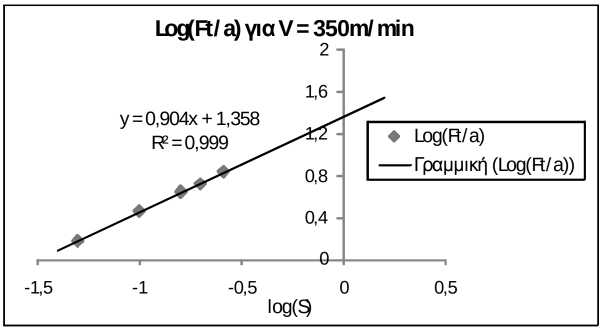

Figure 2. Linear correlation between Log(F_t/a) to Log(s) for cutting speed 350 m/min

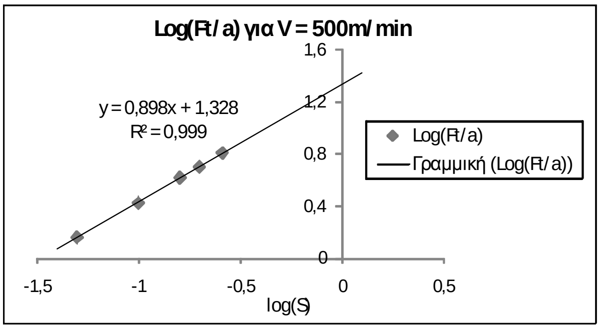

Figure 3. Linear correlation between Log(F_t/a) to Log(s) for cutting speed 500 m/min

Then, similarly, the constants associated with the cutting speed v and inserted in equation (2) as a function thereof. Applying logs in the values of Table 5, we obtained values summarized in Table 6.

Table 6. Log(k_{st1}) and Log(1-z_t) according to Log(v)

v (m/min)	log(v)	Log(k_{st1})	Log(1-z_t)
200	2.301	1.398	-0.041
350	2.544	1.358	-0.044
500	2.699	1.328	-0.047

From the data presented in Table 5 the following figures 4 and 5 are constructed.

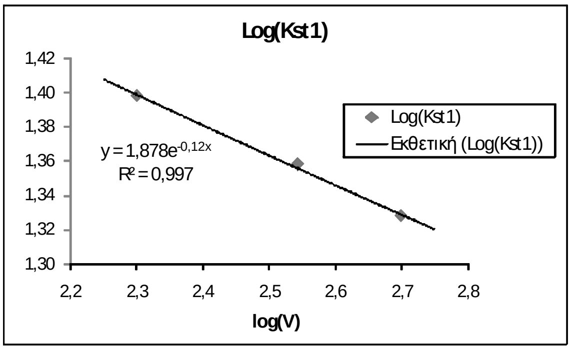

Figure 4. Logarithmic correlation between Log (k_{st1}) and Log(v)

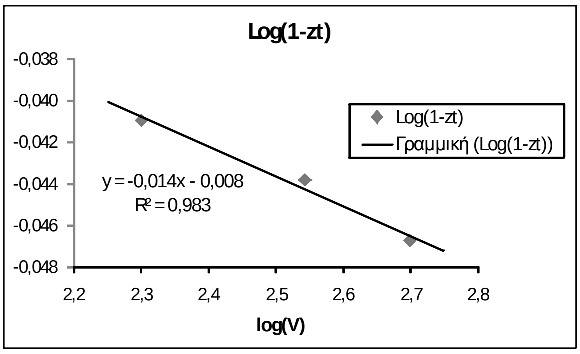

Figure 5. Linear correlation between log(1-z_t) and Log(v)

From the above figures 4 and 5 representing the correlation of Log(k_{st1}) and Log(1-z_t) with Log(v), respectively and since the correlation coefficient R^2 is quite satisfactory for both cases, the final values of the specific cutting resistance k_{st1} and the term (1-z_t) are calculated as a function of the cutting speed:

$$k_{st1} = 10^{1.878 e^{-0.12 \log(v_i)}} \tag{3}$$

$$(1 - z_t) = v_i^{-0.014} 10^{-0.008} \tag{4}$$

Note that, v_i are the values of cutting speeds (200, 350 and 500 m/min).

Finally, from the equations (2), (3), and (4) the main cutting force for each combination of cutting parameters can be calculated; see Table 7.

Table 7. Calculation of the main cutting force component F_t through Kienzle-Victor model and experimentally identified and fixed K_{st1} (1 - z_t)

v (m/min)	s (mm/rev)	K_{st1} (daN/mm^2)	(1 – z_t)	F_t Kienzle (N)	ERFt	% ERFt
200	0.05	26.67	0.912	34.76	1.64	4.95
200	0.1	26.67	0.912	65.40	5.16	8.57
200	0.16	26.67	0.912	100.37	4.81	5.03
200	0.2	26.67	0.912	123.01	7.93	6.89
200	0.26	26.67	0.912	156.25	8.36	5.65

v (m/min)	s (mm/rev)	K_{st1} (daN/mm^2)	$(1 - z_t)$	F_t Kienzle (N)	ERFt	% ERFt
350	0.05	24.28	0.904	32.32	2.08	6.88
350	0.1	24.28	0.904	60.51	2.73	4.72
350	0.16	24.28	0.904	92.56	4.78	5.45
350	0.2	24.28	0.904	113.26	8.65	8.27
350	0.26	24.28	0.904	143.59	7.66	5.64
500	0.05	22.90	0.900	30.90	1.79	6.15
500	0.1	22.90	0.900	57.66	4.59	8.65
500	0.16	22.90	0.900	88.02	5.23	6.32
500	0.2	22.90	0.900	107.59	7.75	7.76
500	0.26	22.90	0.900	136.24	8.42	6.59
			R^2:	97.84%	Average:	6.5%

Note that in Table 7 the difference between measured; see Table 1 and calculated through Kienzle-Victor model, main cutting force values - for all machining conditions, are also presented (see columns ERFt and % ERFt). Agreement obtained is, in general, very good.

The same conclusion can be depicted from the plot presented in Figure 6, in which the difference between the calculated values of the main component of the specific resistance cut energy is compared with the actual values of the experimental measurements.

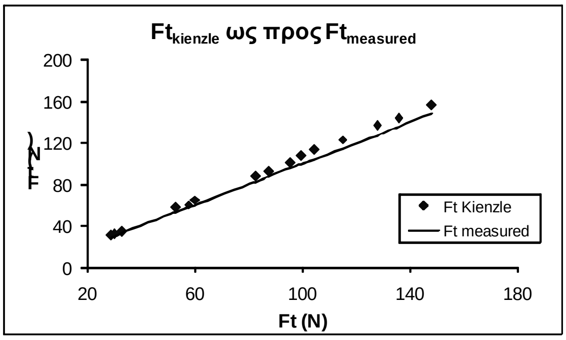

Figure 6. Calculated values of the main component of the cutting force F_t through the semi-empirical model Kienzle-Victor ($F_{t\text{Kienzle}}$), to the actual values of the experimental data ($F_{t\text{measured}}$)

Analysis presented above for the estimation of K_{st1} and $(1\text{-}z_t)$ constants and the prediction of main cutting force according to Kienzle-Victor model can be also applied for the other two components of the 3-D cutting force system i.e., passive and feed force. In this case, however, higher deviations should be expected; see also [8].

5. Conclusions

K_{st1} and $(1\text{-}z_t)$ constants of the Kienzle - Victor cutting force model were determined using experimental data for dry longitudinal turning of the GFRP (Ertalon 66 GF-30®) composite.

It was concluded that the Kienzle-Victor cutting force model can be used in order to predict cutting forces during longitudinal turning of Ertalon 66 GF-30 composite. Agreement obtained is, in general, very good.

References

1. Kechagias, J., Petropoulos, G., Iakovakis, V., Maropoulos, S. (2009) *An investigation of surface texture parameters during turning of a reinforced polymer composite using design of experiments and analysis*. International Journal of Experimental Design and Process Optimisation, Vol. 1, No. 2/3, p. 164-177, ISSN 2040-2252
2. Ntziantzias, J., Kechagias, J., Pappas, M., Vaxevanidis, N.M. (2011) *An experimental study of cutting force system during turning of a glass fiber reinforced polymer composite*. Proceedings of the 4th International Conference on Manufacturing Engineering – ICMEN, ISBN 960-243-615-8, 5-7 October 2011, Thessaloniki, Greece
3. Sarma, P.M.M.S., Karunamoorthy, L., Palanikumar, K. (2008) *Modeling and analysis of cutting force in turning of GFRP composites by CBN tools*. Journal of Reinforced Plastics and Composites, Vol. 27, No. 7 (May 2008), p. 711-723, ISSN 0731-6844
4. Davim, J.P., Silva, L.R., Festas, A., Abrao, A.M. (2009) *Machinability study on precision turning of PA66 polyamide with and without glass fiber reinforcing*. Materials and Design, Vol. 30, No. 2 (February 2009), p. 228-234, ISSN 0261-3069
5. Kienzle, O. (1952) *Die Bestimmung von Kräften und Leistungen an spänenden Werkzeugen und Werkzeugmaschinen* (*Determination of forces and productivity of tools used for machine-tools*). VDI-Z 94 (11/12), p. 299-305 (in German)
6. Victor, H. (1956) *Beitrag zur Kenntnis der Schnittkräfte beim Drehen, Hobeln und Bohren* (*Contribution to the science of the cutting forces in turning, planning and drilling*). Ph.D. thesis. University of Hannover, Hannover, Germany, 1956 (in German)
7. Shaw, M.C. (2004) *Metal Cutting Principles*. Oxford University Press, 2nd ed., ISBN 9780195142068 Oxford, United Kingdom
8. Denkena, B., Köhler, J. (2010) *Consideration of the form of the undeformed section of cut in the calculation of machining forces*. Machining Science and Technology, Vol. 14, No. 4 (December 2010), p.455-470, ISSN 1091-0344