ARPN Journal of Engineering and Applied Sciences

EMPIRICAL STUDY ON STRESS DISTRIBUTION ZONE DURING MACHINING OF DRACS USING FINITE ELEMENT ANALYSIS, TAGUCHI'S DESIGN OF EXPERIMENTS AND RESPONSE SURFACE METHODOLOGY

Raviraj Shetty, Augustine B.V. Barboza and Laxmikanth G. Keni
[1]Department of Mechanical and Manufacturing Engineering, Manipal Institute of Technology, Manipal University, Karnataka, India
[2]Department of Aeronautical and Automobile Engineering, Manipal Institute of Technology, Manipal University, Karnataka, India
E-Mail: rr.shetty2@rediffmail.com

ABSTRACT

Today's World manufacturing industries is widely focusing on numerical, statistical and analytical methods. In this paper, three of those methods have been employed namely finite element analysis, Taguchi's design of experiments and response surface methodology. Initially stress distribution in primary and secondary deformation zone in machining of DRACs was conducted using finite element analysis based on Taguchi's design of experiments. The experimental results were then correlated using Taguchi method, for identification of optimum cutting parameters followed by mathematical model using Response Surface Methodology (RSM).

Keywords: discontinuously reinforced aluminium composites (DRACs); stress; finite element analysis; design of experiments; response surface methodology; ANOVA.

ABBREVIATIONS:

σ_y	: Yield stress
σ_o	: Initial yield stress
ε_s	: Strain rate
C and P	: Cowper-Symonds parameters for strain rate
ε_{eff}	: Effective plastic strain.
β	: Hardening parameter.
E_P	: Plastic hardening modulus
E_{tan}	: Tangent modulus.
E	: Modulus of elasticity
τ_{lim}	: Limiting shear stress
τ	: Equivalent shear stress
P	: Contact pressure
μ	: Friction of coefficient
b	: Cohesion sliding resistance
APDL	: Ansys Parametric Design Language
F	: Fishers Test
P	: Probability Statistic
ANOVA	: Analysis of Variance
RSM	: Response Surface Methodology
DF	: Degrees of Freedom
Seq SS	: Sequential Sum of Squares
Adj SS	: Adjusted Sum of Squares
Adj MS	: Adjusted Mean of Squares

INTRODUCTION

Turning is the most common method used in metal cutting industries for manufacture of low cost, high quality products in short time. Stress induced in primary and secondary deformation zone is easiest way of analyzing the cutting conditions in spite of cutting speed, feed, and depth of cut, rake angle the material and cutting tool properties. Restrictions concerning the stress distribution during machining of DRACs is of major concern.

Since last three decades there was very few literature related to the finite-element simulation as far as stress distribution is concerned. A revolutionary piece of work was carried out to predict chip shape, and stress and strain distributions and Chip fracture [1] [2] used ANSYS software for analyzing chip formation and machined surface. [3] Carried out diamond turning of 6061 aluminum silicon carbide composites using dynamic finite-element analysis. [4] Carried out orthogonal machining of 6061 aluminium aluminum oxide composite using a tungsten carbide tool. [5] Developed a quasi static finite element code of chip separation criterion in orthogonal cutting of discontinuously reinforced aluminium composites. [6] in their work suggested that thermal load effect and residual stress could be ignored for certain cutting parameter ranges. [7] Observed that the critical value for chip separation based on energy density is a material constant and is independent of uncut chip thickness.

The main problem while machining of DRACs is tool wear and uneven stress distribution [8-10].

The purpose of this paper is to investigate stress distribution in primary and secondary deformation zone during machining of DRACs and generation of mathematical model.

EXPERIMENTAL DETAILS

The L_{27} orthogonal array was selected, which has 27 rows corresponding to the number of tests with 13 columns at three levels. The output to be studied was the stress in primary and secondary deformation zone which was obtained using finite element analysis as shown in

Figure-1. Further an analysis of variance (ANOVA) was carried out for stress. Finally a second-order model has been established between the cutting parameters and stress using response surface methodology. The steps of our study of optimization are presented in Figure-2. The selected levels and factors in machining of DRACs are shown in Table-1.

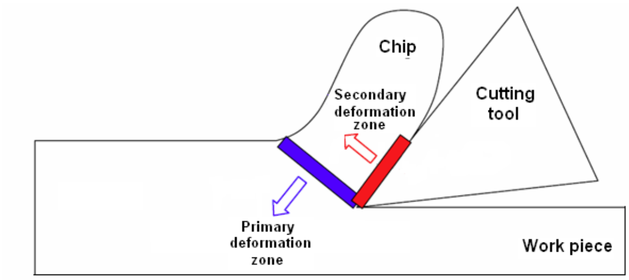


Figure-1. Stress measured at different deformation zones in machining of DRACs using finite element analysis.

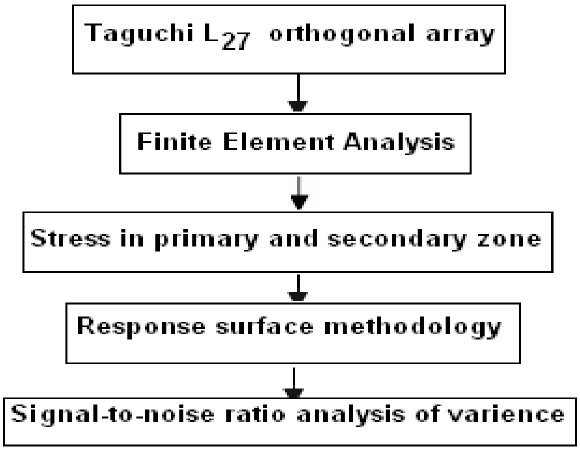


Figure-2. Steps of the optimization process.

Table-1. Levels and factors.

Levels	(A) Cutting speed (m/min)	(B) Depth of cut (mm)	(C) Rake angle(deg)
1	45	0.25	-5
2	73	0.50	0
3	101	0.75	+5

Finite element modeling

In this section material modeling, boundary conditions, contact and friction used for machining of DRACs are discussed. Further influence of cutting parameters on stress distribution in primary and secondary deformation zone based on Taguchi's Design of Experiments will be studied. These parameters include Cutting speed, Depth of cut and Rake angle.

Material Modeling

The DRACs work material was a 6061 aluminum alloy reinforced with 25μm silicon carbide particles size was modeled using the Cowper-Symonds model. According to ANSYS/LSDYNA manual [11] the equation to calculate yield stress in the plastic kinematics material model is given below:

$$\sigma_y = \left[1 + \left(\frac{\dot{\varepsilon}}{C}\right)^{1/P}\right]\left(\sigma_0 + \beta E_P \varepsilon_{sP}^{eff}\right)$$

Where

$$E_P = \left(\frac{E_{\tan} E}{E - E_{\tan}}\right)$$

The material properties of the matrix were based on the commonly accepted values σ_0=125 MPa, E=71 GPa, E_{tan} = 1.48 GPa from [12-13] values of Cowper-Symonds strain rate parameters (C = 6500, P= 4) for aluminum alloy were taken form ANSYS/LSDYNA manual. Based on the work for aluminum alloys reported in [14] the limiting strain was taken as 1.

Boundary Conditions

A two-dimensional finite element model was constructed using explicit finite element software package ANSYS/LSDYNA, version 11. The cutting tool was treated as a rigid body and moved horizontally into the workpiece at three different speeds i.e. 45m/min, 73m/min and 101m/min, depth of cut 0.25mm,0.5mm,0.75mm and rake angle -5°, 0°,+5°. The workpiece was fully fixed on its bottom surface to eliminate rigid body motion.

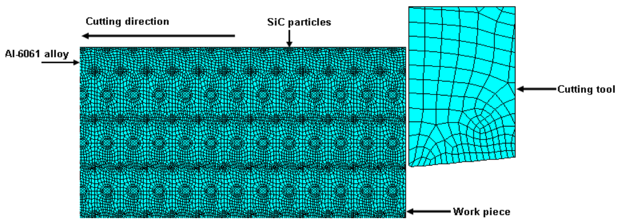


Figure-3. Finite element mesh for DRACs.

Contact and friction [25]

Along with the general contact family in ANSYS/LSDYNA, the automatic contact options are the most commonly used contact algorithms for its versatility. Hence, 2D automatic contact was chosen for this simulation. In order to consider the effect of friction along the tool–chip interface, Coulomb friction model was employed. This is defined as

$$\tau_{\lim} = \mu P + b$$

$$|\tau| \leq \tau_{\lim}$$

The limiting shear stress τ_{lim}= 202 MPa and coefficient of friction, μ=0.62 were based on the study reported in [25].

ARPN Journal of Engineering and Applied Sciences

Taguchi's DOE method

Taguchi's DOE techniques have been used widely in engineering design [16-17] The main trust of the Taguchi's DOE techniques is the use of parameter design, which is an engineering method for product or process design, that focuses on determining the parameter (factor) settings producing the best levels of a quality characteristic (performance measure) with minimum variation [17-24].

Response surface methodology

The stresses generated during machining of DRACs have considerable effect on tool wear and surface finish. In order to know the stresses in advance, it is necessary to employ theoretical models making it feasible to predict function of operation conditions [22-24].

RESULTS AND DISCUSSIONS

Von-Mises stress distribution in primary and secondary deformation zone [25]

Von-Mises stress distribution under different cutting parameter based on Taguchi's orthogonal array is shown in the Figure-4. During the orthogonal machining of DRACs, the chip is formed by shearing in the primary deformation zone. As a result of very high shear stresses and pressures at the chip tool interface, a secondary deformation zone along the chip tool interface also occurs. The Von-Mises stress was found to have highest value in the primary deformation zone which is due to the compressive stress exerted by the cutting tool tip.

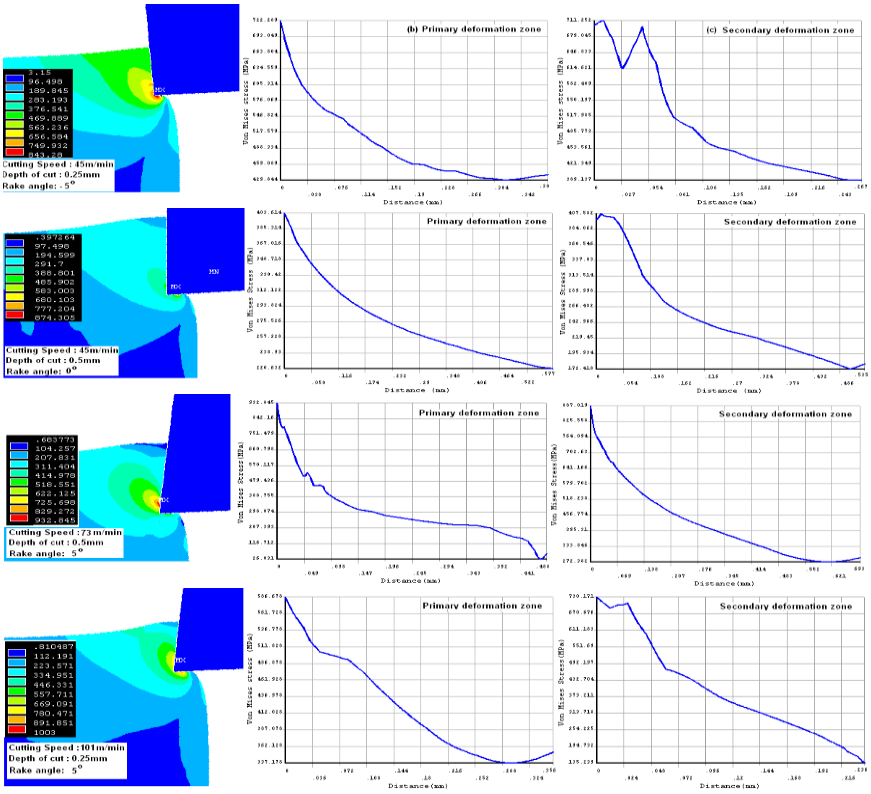


Figure-4. Finite element analysis of stress distribution in primary and secondary deformation zone during machining of DRACs.

Effect of cutting parameters on stress distribution

In Taguchi's DOE method, the term "signal" represents the desirable value and "noise" represents the undesirable value. The objective of using S/N ratio is to obtain a measure of performance to develop products and processes insensitive to noise factors. Table-2 and Table-3 shows the S/N ratios obtained for different parameter levels.

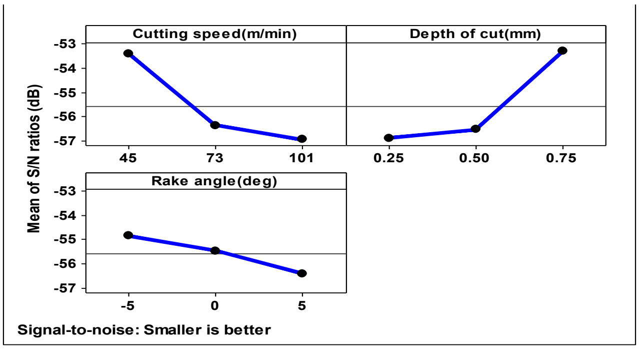


Figure-5. Mean S/N graph for stress distribution in primary deformation zone.

ARPN Journal of Engineering and Applied Sciences

Table-2. Response table for Signal to Noise ratios Smaller is better (maximum primary stress).

Level	(A) Cutting speed (m/min)	(B) Depth of cut (mm)	(C) Rake angle (deg)
1	-53.40	-56.90	-54.85
2	-56.37	-56.55	-55.46
3	-56.96	-53.29	-56.42
Delta	3.56	3.61	1.57
Rank	2	1	3

Table-3. Response table for Signal to Noise ratios Smaller is better (maximum secondary stress).

Level	(A) Cutting speed (m/min)	(B) Depth of cut(mm)	(C) Rake angle (deg)
1	-53.45	-57.03	-54.99
2	-56.48	-56.62	-55.39
3	-57.06	-53.35	-56.62
Delta	3.61	3.68	1.63
Rank	2	1	3

Table-4. Analysis of Variance for S/N ratios for primary stress.

Source	DF	Seq SS	Adj MS	F	P	P (%)
(A) Cutting speed (m/min)	**2**	**65.533**	**32.7663**	**132.80**	**0.0**	**32.96**
(B) Depth of cut (mm)	2	71.476	35.7381	144.84	0.0	35.94
(C)Rake angle(deg)	2	11.231	5.6154	22.76	0.0	5.65
AxB	4	100.628	25.1569	101.96	0.0	25.30
AxC	4	0.547	0.1367	0.55	0.7	0.14
BxC	4	0.064	0.0160	0.06	0.9	0.01
Residual Error	8	1.974	0.2467			
Total	26	251.452				100

Table-5. Analysis of Variance for S/N ratios for secondary stress.

Source	DF	Seq SS	Adj MS	F	P	P (%)
(A) Cutting speed (m/min)	**2**	**67.7**	**33.8970**	**82.8**	**0.0**	**33.49**
(B) Depth of cut (mm)	2	73.3	36.6778	89.5	0.0	36.24
(C) Rake angle (deg)	2	12.9	6.4833	15.8	0.0	6.41
AxB	4	94.8	23.7040	57.9	0.0	23.42
AxC	4	1.44	0.3611	0.88	0.5	0.36
BxC	4	0.35	0.0877	0.21	0.9	0.08
Residual Error	8	3.27	0.4094			
Total	26	254				100

The calculated S/N ratio for three factors on the stresses in primary and secondary deformation zone during machining of DRACs for each level is shown in (Figure-5-Figure-6). As shown in (Table-2, Table-3) and (Figure-5, Figure-6) depth of cut is a dominant parameter on the stress followed by cutting speed. The rake angle had a lower effect on the stresses. The quality characteristic considered in the investigation is “smaller the better”. In the present investigation, when the depth of cut is at 0.25mm,cutting speed is at 101m/min and 5 deg rake angle the stresses was minimum in both primary and secondary deformation zone.

On the examination of the percentage of contribution (P%) of the different factors (Table-5, Table-6), for stress in primary and secondary deformation zone it can be seen that depth of cut has the highest contribution of about 35.94% in primary deformation zone and secondary deformation zone of about 36.24%, Followed by cutting speed and rake angle. Further Interactions (AxC), (BXC) do not present a statistical significance, nor a percentage of physical significance of contribution to the stress in primary and secondary deformation zone.

ARPN Journal of Engineering and Applied Sciences

Stress distribution model

The second order response surface representing the maximum stress in primary deformation and secondary deformation zone can be expressed as a function of cutting parameters. The relationship between the maximum stress and cutting parameters has been expressed as follows:

$$\text{Stress} = \beta_o + \beta_1 A + \beta_2 B + \beta_3 C + \beta_4 A^2 + \beta_5 B^2 + \beta_6 C^2 + \beta_7 AB + \beta_8 AC + \beta_9 BC + \varepsilon$$

From the observed data for maximum stress, the response function has been determined in uncoded units as:

$$\text{Maximum Stress in primary deformation zone} = 146.762 + 12.8195A + 728.160B + 5.57543C - 0.138966A^2 - 2595.95B^2 + 2.03842C^2 + 20.1962AB + 0.0655688AC - 1.23890BC$$

$$\text{Maximum Stress in secondary deformation zone} = -387.114 + 27.5002A + 1055.71B - 19.9473C - 0.220616A^2 - 2566.28B^2 + 3.25602C^2 + 13.3770AB + 0.438442AC + 13.9715BC$$

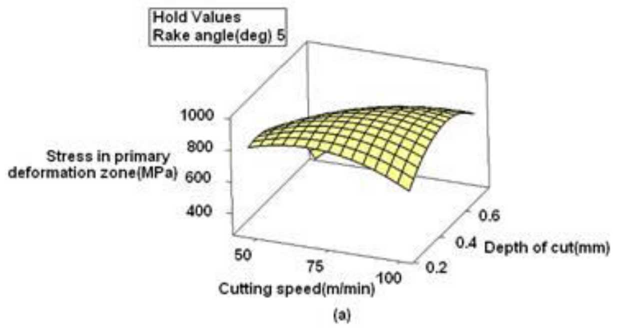
Result of ANOVA for the response function stress in primary and secondary deformation zone is presented in Table-6 and Table-7. Surface plot of stresses in primary deformation zone at cutting speed - depth of cut planes is shown in Figure-7.

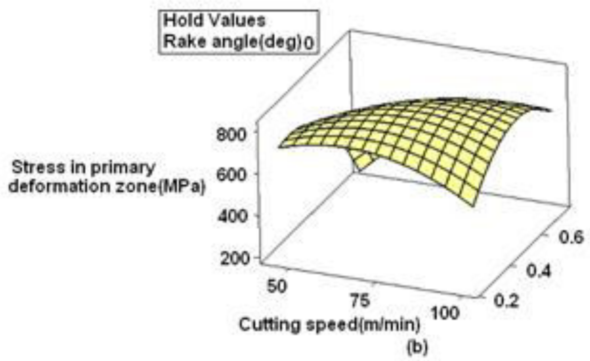
Table-6. ANOVA table for response function of the maximum stress in primary deformation zone.

Source	DF	Seq SS	Adj MS	F	P
Regression	9	562340	62482.2	5.96	0.005
Residual error	10	104782	10478.2		
Total	19	667122			

Table-7. ANOVA table for response function of the maximum stress in secondary deformation zone.

Source	DF	Seq SS	Adj MS	F	P
Regression	9	717336	79704	9.26	0.001
Residual Error	10	86103	8610		
Total	19	803439			





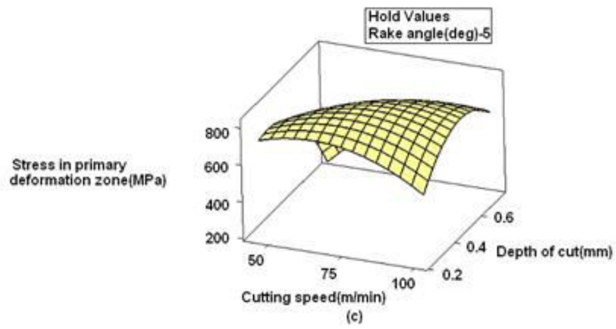


Figure-6. Surface plot of stress distribution in primary deformation zone at cutting speed- depth of cut planes.

Confirmatory experiments

To predict and verify the improvement in the stress for machining of DRACs by the turning process with respect to the chosen initial parameter setting, verification tests are used. (Figure-7, Figure-8) shows the validation of FEM results for the stress in primary and secondary deformation zone. Test numbers 1 to 27 shows the comparison of FEM results with mathematical model results obtained from Eq. (8). The result shows that the predicted value is the fairly close for all tests.

ISSN 1819-6608

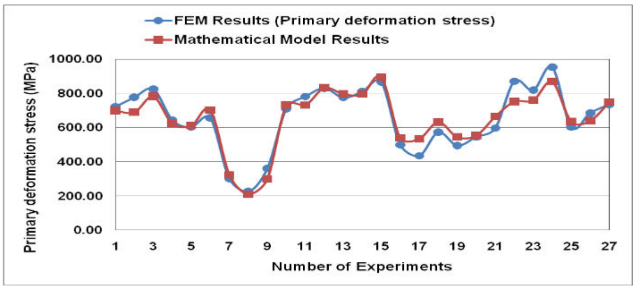


Figure-7. Verification test results for primary deformation stress.

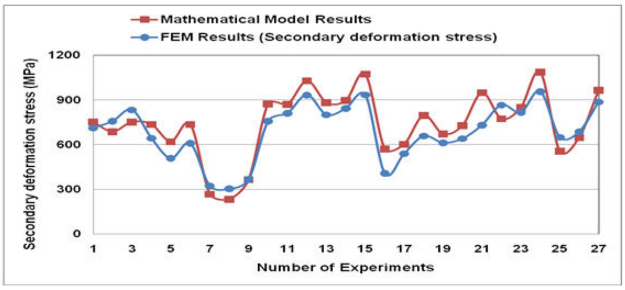


Figure-8. Verification test results for secondary deformation stress.

CONCLUSIONS

An application of finite element analysis, Taguchi's design of experiments and response surface methodology on stresses induced in primary and secondary deformation zone on orthogonal cutting of DRACs was performed in the present investigation. The reasonable agreement obtained between the finite element analysis, Taguchi's design of experiments and response surface methodology results indicate that the proposed method appears to be suitable for studying the influence of cutting parameters on stress arising from machining. The following conclusions can be drawn from our investigation:

- In the study, for a given stress profile obtained from finite element analysis, the technique supplies the possible cutting parameters, compatible with this profile. What is more, a proper optimization process is able to supply the best result taking into account a defined goal function.
- The effect of cutting parameters on the stress in primary and secondary deformation zone has been evaluated with the help of Taguchi method and optimal machining conditions to minimize the stress have been determined.
- The depth of cut is the dominant parameter for stress followed by the cutting speed. Rake angle shows minimal effect on stress compared to other parameters.
- A mathematical model has been successfully developed to predict stress in primary and secondary deformation zone of DRACs incorporating the effects of cutting speed, depth of cut and rake angle.
- The response surface methodology can generalize these results in order to have a quick prediction of the stress distribution in primary and secondary deformation zone.
- A second-order response surface model for stress has been developed from the finite element analysis. The predicted and finite element values are fairly close, which indicates that the developed model can be effectively used to predict stress distribution in primary and secondary deformation zone on the machining of DRACs with 95% confidence intervals.

REFERENCES

[1] K.Iwata, K. Osakada, Y. Terasaka. 1984. Process modeling of orthogonal cutting by rigid-plastic finite element method. Journal of Engineering Materials and Technology, Transactions of ASME. 106: 132-138.

[2] J. Monaghan, D. Brazil. 1998. Modelling the flow processes of a particle reinforced metal matrix composite during machining. Composites. 29A: 87-99.

[3] M.V. Ramesh, K.C. Chan, W.B. Lee, C.F. Cheung. 2001. Finite-element analysis of diamond turning of aluminium matrix composites. Composites Science and Technology. 61: 1449-1456.

[4] Y. Zhu, H.A. Kishawy. 2005. Influence of alumina particles on the mechanics of machining metal matrix composites. International Journal of Machine Tools and Manufacturing. 45: 389-398.

[5] Raviraj. Shetty, R.B. Pai, S.S. Rao, B.S. Shenoy. 2006. Application of finite element analysis in orthogonal cutting of aluminium metal matrix composites, in; Proceedings of International conference on Advances in Mechanical Engineering, (ICAME 2006), Chennai, India.

[6] Z.C. Lin, Y.Y. Lin, C.R. Liu. 1991. Effect of thermal load and mechanical load on the residual stress of a machined surface, International Journal of Mechanical Sciences. 33: 263-278.

[7] Z.C. Lin, S.Y. Lin. 1992. A coupled finite element model of thermo-elastic-plastic large deformation for orthogonal cutting. Journal of Engineering Materials and Technology, Transactions ASME. 114: 218-226.

[8] T.Beard. 1998. Machining composites-new rules and tools. Modern Machine Shop. 619110: 74-85.

[9] P.G. Berrie, F.N. Birkett. 1980. The drilling and cutting of polymethyl methacrylate (Perpex) by CO_2

laser, Optics and Laser in Engineering. Applied Science Publisher Ltd, England. 107-129.

[10] G. Caprino, V. Tagliaferri. 1995. Damage devolvement in drilling glass fiber reinforced plastics. International Journal of Machine Tool and Manufacturing. 35(6): 817-829.

[11] ANSYS/LS-DYNA Reference Manual, Release 10, Livermore Software Technology Corporation, Livermore, CA. www.lstc.com.

[12] G.Meijer, F. Ellyin,Z. Xia. 2000. Aspects of residual thermal stress/strain in particle reinforced metal matrix composites, Composites: Part B, 31: 29-37.

[13] 13. S.G.Long, Y.C.Zhou. 2005. Thermal fatigue of particle reinforced metal–matrix composite induced by laser heating and mechanical load. Composites Science and Technology. 65: 1391-1400.

[14] Z.F.Zhang, L.C Zhang, Y.W.Mai. 1995. Particle effects on friction and wear of aluminium matrix composites, Journal of Materials Science. 30(23): 5999-6004.

[15] A. Pramanik, l.C. Zhang, J.A. Arsecularatne. 2006. Prediction of cutting forces in machining of metal matrix composites. International Journal of Machine Tools and Manufacturing. 46: 1795-1803.

[16] M.S.Phadke. 1989. Quality engineering using robust design. Englewood Cliffs, NJ: Prentice-Hall.

[17] W.H Yang, Y.S. Tarng. 1998. Design optimization of cutting parameters for turning operations based on the Taguchi method. Journal of Material Processing Technology. 84: 122-129.

[18] Y.L. Su, S.H. Yao, C.S. Wei, W.H. Kao, C.T Wu. 1999. Design and performance analysis of TiCN-coated cemented carbide milling cutters. Journal of Material Processing Technology. 87: 82-89.

[19] C.Y Nian, W.H. Yang, Y.S. Tarng. 1999. Optimization of turning operations with multiple performance characteristics. Journal of Material Processing Technology. 95: 90-96.

[20] J.P Davim. 2003. Design optimization of cutting parameters for turning metal matrix composites based on the orthogonal arrays. Journal of Material Processing Technology. 132: 340-344.

[21] J.A Ghani, I.A. Choudhury, H.H Hassan. 2004. Application of Taguchi method in the optimization of end milling operations. Journal of Material Processing Technology. 145: 84-92.

[22] D.C. Montgomery. 1984. Design and analysis of experiments, New York: John Wiley and Sons.

[23] P.J. Ross. 1996. Taguchi techniques for quality engineering: loss function, orthogonal experiments, parameter and tolerance design. 2^{nd} ed. New York: McGraw-Hill.

[24] Raviraj Shetty, Raghuvir Pai, Srikanth S. Rao and Vasanth Kamath. 2008. Machinability study on discontinuously reinforced aluminium composites (DRACs) using response surface methodology and Taguchi's design of experiments under dry cutting condition, Mj. Int. J. Sci. Tech. 2(01): 227-239

[25] Shetty, Raviraj, Keni, Laxmikanth, Pai, Raghuvir, B and Kamath, Vasanth. 2008. Experimental and analytical study on chip formation mechanism in machining of DRACs. ARPN Journal of Engineering and Applied Sciences. 3(5): 27-32.