Cylindrical grinding process parameters optimization of Al / SiC metal matrix composites

C. Thiagarajan[a*], S. Ranganathan[b] and P. Shankar[c]
[a, b, c]Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha University, Chennai-602105, Tamilnadu, India.

Abstract—The present investigation reports the effects of the grinding process parameters namely wheel velocity, work piece velocity, feed rate and depth of cut in grinding of Al/SiC composites on grinding force, surface roughness and grinding temperature. The optimum values are obtained by employing Taguchi method. Combined effects of the four process parameters i.e wheel velocity, work piece velocity, feed rate and depth of cut on the performance measures grinding force, surface roughness, grinding temperature were investigated by using an orthogonal array and the analysis of variance (ANOVA) in grinding of Al/SiC composites. Optimal process parameters for each performance measures were obtained using S/N ratio. The S/N ratio values are calculated for each factor at a given level, allow the establishment of the best levels for predicting the grinding force, surface roughness and grinding temperature.

Keywords: Cylindrical grinding, grinding force, surface roughness, grinding temperature, S/N ratio and ANOVA.

1 Introduction

Aluminium alloys reinforced with silicon carbide particles are potentially useful structural materials, with high strength, high modulus values, and are used in various industrial applications. These applications warrant machining of the composites. Despite all these large applications, the Al/SiC composites are difficult to machine to a good surface finish. The main concern in machining of Al/SiC composites is the extremely high tool wear, due to the abrasive action of the SiC particles and needs to be addressed for the successful application of these composites. Sun et al reported that, the grinding is an important finish-machining process that is widely used in the manufacture of components requiring fine tolerances and smooth finish. Since the problems associated with the machining of Al/SiC composites are large, they cannot be applied with ease [1]. The grinding problems can be minimized, if not eliminated by the careful selection of appropriate grinding parameters and other important conditions, like the percentage of SiC volume fraction to improve the surface finish. Methods to produce the Al/SiC composites and studies on their machining characteristics have been reported [2-4]. The presence of SiC in the metal matrix is reported to increase the hardness, tensile strength and heat resistance of the composites.

The corresponding author Dr. C. Thiagarajan is currenly Professor in Department of Mechanical Engineering, Saveetha School of Engineering, Saveetha University, Chennai-602105, Tamilnadu, India.
thiaguresearch@gmail.com, Phone: +91 9445262985

However during the machining of Al/SiC composites using conventional methods, the presence of hard SiC particles causes problems like cracking and splintering [5]. Anand Ronald et al studied the grinding with resin bonded and plated diamond abrasive wheels to evaluate the significance of bond on wheel performance and reported that resin bonded wheel gave better surface finish compared to the electroplated wheel [6]. Slowik and Slowik presented the multi objective optimization of a surface grinding process using evolutionary algorithm [7]. Saravanan et al reported the genetic algorithm based optimization procedure to optimize the grinding conditions [8]. Zhong et al studied the grinding of Al/Al_2O_3 MMCs using grinding wheels having SiC in a vitrified matrix and diamond in a resin-bonded matrix and discussed the surface roughness, grinding force, type and size of the abrasives, grinding conditions, and the consequential sub-surface integrity [9]. Shaji and Radhakrishnan investigated the analysis of process parameters in surface grinding with graphite lubricant based on the Taguchi method [10]. Nalbany et al finds the optimal cutting parameters for surface roughness in turning using Taguchi method [11]. Yang and Tarng reported that the Taguchi method is effective approach in optimization of cutting parameters for turning of S45C steel [12]. Chen et al presented the optimized process parameters on machining of EDM using Taguchi method [13]. Taguchi method is powerful approach to optimize the process parameter and efficient method over a variety of operating conditions. In this study, Taguchi based L27 orthogonal array was selected to optimize the cylindrical grinding process parameters for Al/SiC composites.

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2. EXPERIMENTAL DETAILS

2.1 Fabrication of Workpiece

Al/SiC composite specimens were fabricated by the addition of SiC reinforcement (particle size 13 µm) to the LM25 aluminium alloy matrix with the dimensions of ϕ30 × 200 mm. The chemical composition of the LM25 aluminium alloy is given in Table 1

Table 1 Chemical composition of the LM25 aluminium alloy

Elements	Cu	Si	Mg	Mn	Fe	Ni	Ti	Zn	Pb	Sn
Composition (%)	0.2	6.5-7.5	0.2-0.6	0.3	0.5	0.1	0.2	0.1	0.1	0.05

This composite can be synthesized more easily by the stir casting process since stir casting is a relatively inexpensive processing method, and offers a wide selection of materials and processing conditions and involves the addition of SiC particles into the semi-solid aluminium metal by means of agitation (stirring). The Al/SiC specimens in the 'as-cast' condition and the stir casting set-up used to fabricate them, are shown in Figures 1 and 2 respectively.

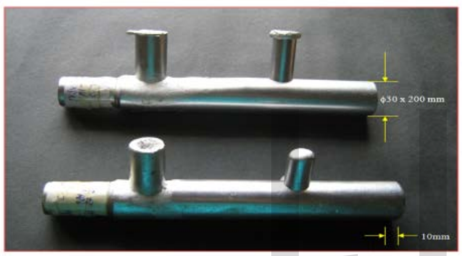


FIGURE 1 LM25AL/SIC SPECIMENS

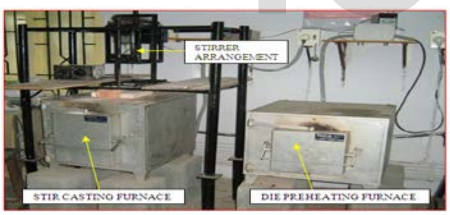


FIGURE 2 STIR CASTING SET-UP

The SEM micro structure of the LM25Al/SiC in Figure 3 shows the uniform distribution of the SiC particles in the aluminium matrix and EDX analysis ascertained the presence of the SiC particles in the metal matrix. As far as the machining of SiC is concerned, Al_2O_3 grinding wheel is a better choice for grinding of Al/SiC composites.

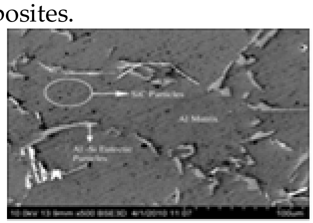
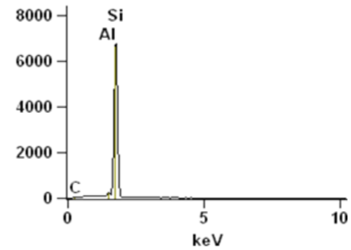


FIGURE 3. UNIFORM DISTRIBUTION OF THE SiC PARTICLES IN THE ALUMINIUM MATRIX



2.2 Cylindrical grinding set-up

The experiments were carried out as per L27 orthogonal array with three levels defined for each of the four process parameters. Grinding performance of Al/SiC composites was studied by conducting various machinability tests using Al_2O_3 grinding wheel. The experiments were conducted on horizontal spindle cylindrical grinding machine (Type G13P, HMT make) and the setup is shown in Figure 4.

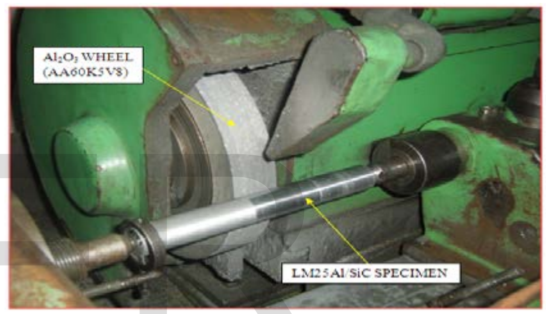


FIGURE 4 CYLINDRICAL GRINDING SET-UP

Based on the Taguchi's orthogonal array, the experiments were conducted by varying the four parameters, namely, the wheel velocity (V_w), workpiece velocity (V_c), feed (f) and depth of cut (a_P) at three levels. The grinding conditions adopted in the present study are shown in Table 2.

Table 2 Grinding conditions and their levels

Parameters	Levels		
	1 Low	2 Medium	3 High
Wheel velocity, V_w (m/min)	1414	2026	2639
Workpiece velocity, V_c (m/min)	6.11	12.72	26.72
Feed rate- Work table traverse, f (m/min)	0.06	0.09	0.17
Depth of cut, a_P (µm)	10	20	30

2.3 Measurement of Grinding Responses

A device called VFD (ACS 350-03E-12A5-4, ABB make) was used to measure the power of the grinding wheel motor to calculate the tangential grinding force (F_t). The surface roughness (R_a) of the ground specimens was measured in the direction perpendicular to the grinding direction, using a stylus based surface roughness tester (Surfcorder-SE1200) is shown in Figure 5. A non-contact infrared thermometer (METRAVI make) was used to measure the grinding zone temperature (T_g) is shown in Figure 6. The

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results of experiment of grinding of Al/SiC composites are shown in the Table 3.

FIGURE 5 SURFACE ROUGHNESS TESTER

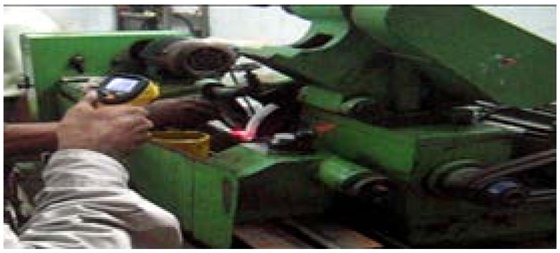


FIGURE 6 NON-CONTACT INFRARED THERMOMETER

Table 3 Experimental results

No	v_w	v_c	f	a_p	F_t	S/N ratio	R_a	S/N ratio	T_g	S/N ratio
1	1	1	1	1	20	-26.02	0.41	7.74	740	-57.38
2	1	1	1	2	26	-28.29	0.52	5.68	747	-57.47
3	1	1	1	3	31	-29.82	0.59	4.58	751	-57.57
4	1	2	2	1	26	-28.29	0.53	5.49	759	-57.6
5	1	2	2	2	30	-29.54	0.64	3.76	766	-57.68
6	1	2	2	3	35	-30.88	0.71	2.9	782	-57.86
7	1	3	3	1	24	-27.60	0.37	8.52	782	-57.86
8	1	3	3	2	27	-28.62	0.49	6.09	794	-57.99
9	1	3	3	3	36	-31.12	0.54	5.26	811	-58.18
10	2	1	3	1	19	-28.62	0.39	5.35	757	-57.59
11	2	1	3	2	27	-29.24	0.59	3.22	767	-57.66
12	2	1	3	3	32	-26.44	0.79	6.99	770	-57.51
13	2	2	1	1	19	-28.29	0.23	6.92	767	-57.87
14	2	2	1	2	24	-29.54	0.31	4.12	773	-58
15	2	2	1	3	27	-27.96	0.38	9.82	782	-57.77
16	2	3	2	1	19	-26.85	0.26	11.7	786	-57.91
17	2	3	2	2	25	-28.29	0.33	10.6	792	-58.06
18	2	3	2	3	28	-24.60	0.39	14.1	802	-57.86
19	3	1	2	1	18	-28.94	0.27	5.65	771	-57.93
20	3	1	2	2	22	-24.6	0.43	11.9	779	-57.79
21	3	1	2	3	25	-26.84	0.57	7.68	785	-57.83
22	3	2	3	1	22	-27.6	0.29	10.9	788	-58.08
23	3	2	3	2	24	-24.6	0.34	14.7	805	-57.89
24	3	2	3	3	25	-26.84	0.45	12.7	815	-58
25	3	3	1	1	16	-29.54	0.17	9.47	805	-58.65
26	3	3	1	2	21	-26.02	0.20	14.3	819	-58.34
27	3	3	1	3	23	-26.84	0.22	11.3	829	-58.53

F_t – Tangential Force R_a – Surface roughness T_g – Grinding temperature

3. RESULTS AND DISCUSSIONS

Aluminium alloy with SiC composite materials are finding many applications like aerospace, automotive, marine, building, packaging industries and many engineering components. Grinding of these components cannot be avoided and the experiments are conducted for analyzing the influence of grinding parameters to give the best combination of the machining conditions. Grinding wheel velocity, work piece velocity, feed rate and depth of cut are the major grinding process parameters that are considered in these experiments. Tangential grinding force, surface roughness and grinding temperature were the minimization quantities and should be optimized in terms of the process parameters using S/N ratio [14].

In this study, S/N ratios were calculated using a ‘‘smaller is better’’ approach and its is calculated as follows [14];

$$\text{S/N ratio } \eta = -10 \log \left[\frac{1}{n} \sum_{i=1}^{n} y_i^{\,2} \right]$$

The performance measures namely, Tangential force, surface roughness and grinding temperature were analyzed with analysis of variance (ANOVA). The results of the ANOVA tables 4,5, and 6 shows the Tangential force , surface roughness and grinding temperature and their significant parameters. The analysis was carried out for the confidential level of 95% and the last column shows the percentage contribution of the performance measures.

Table 4 ANOVA for Tangential Grinding Force

Source	DOF (df)	Sum of Squares (SS)	Mean Squares (MS)	p-value Prob > F	Percent (%)
A-Wheel Velocity	2	288.07	144.0	0.0023	51
B- Workpiece Velocity	2	0.96	0.48	0.8783	0.175
C- Feed rate	2	102.74	51.37	0.0151	18.21
D- Depth of cut	2	12.04	6.02	0.2961	2.13
AB	4	75.70	18.93	0.0682	16.42
AC	4	5.93	1.48	0.7940	1.05
Error	4	14.37	3.59		2.47
Total	20	564.07			

Table 5 ANOVA for Surface Roughness

Source	DOF (df)	Sum of Squares (SS)	Mean Squares (MS)	p-value Prob > F	Percent (%)
A-Wheel Velocity	2	0.26	0.13	0.0003	38.24
B- Workpiece Velocity	2	0.12	0.060	0.001	17.65
C- Feed rate	2	0.16	0.080	0.0008	23.53
D- Depth of cut	2	3.523E-4	1.762E-4	0.858	0.518
AB	4	0.12	0.030	0.003	17.65

AC	4	2.849E-3	7.123E-4	0.660	0.419
Error	4	4.43E-3	1.110E-3		0.653
Total	20	0.68			

Table 6ANOVA for Grinding Temperature

Source	DOF (df)	Sum of Squares (SS)	Mean Squares (MS)	p-value Prob > F	Percent (%)
A- Wheel Velocity	2	6357.56	3178.78	0.0001	32
B- Workpiece Velocity	2	10136.00	5068.00	0.0001	51
C- Feed rate	2	1670.89	835.44	0.0009	8.41
D- Depth of cut	2	1.33	0.67	0.9502	0.006
AB	4	1451.11	362.78	0.0035	7.31
Error	4	51.56	12.89		0.256
Total	16	19862.00			

The average S/N ratio values, calculated for each factor at a given level, allow the establishment of the best levels. It was found that the best parameters for tangential force and their levels are A3B1C2D2, for surface roughness A3B3C1D3 and for grinding temperature A1B1C2D1 are shown in table 7,8 and 9.

Table 7.Response table for S/N ratio of grinding force

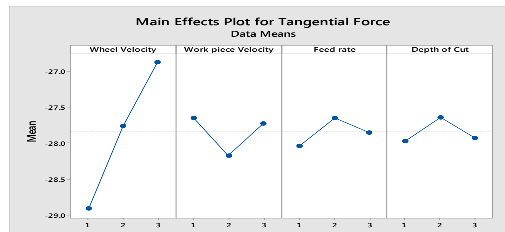
Level	Wheel velocity, V_w (m/min)	Workpiece velocity, V_c (m/min)	Feed rate-Work table traverse, f (m/min)	Depth of cut, a_p (μm)
1	-29.089	-27.645	-28.035	-27.972
2	-27.758	-28.17	-27.647	-27.637
3	-26.868	-27.72	-27.853	-27.926
delta	2.220	0.525	0.388	0.289
Rank	1	2	3	4

Table 8.Response table for S/N ratio of surface roughness

Level	Wheel velocity, V_w (m/min)	Workpiece velocity, V_c (m/min)	Feed rate-Work table traverse, f (m/min)	Depth of cut, a_p (μm)
1	5.5577	6.54	8.23	7.978
2	8.106	7.94	8.22	8.296
3	10.994	10.178	8.208	8.384
delta	5.4363	3.638	0.0211	0.4064
Rank	1	2	4	3

Table 9.Response table for S/N ratio of grinding temperature

Level	Wheel velocity, V_w (m/min)	Workpiece velocity, V_c (m/min)	Feed rate-Work table traverse, f (m/min)	Depth of cut, a_p (μm)
1	-57.732	-57.636	-57.953	-57.874
2	-57.803	-57.861	-57.835	-57.875
3	-58.115	-58.153	-57.8692	-57.9011
delta	0.3835	0.517	0.0907	0.02711
Rank	2	1	3	4



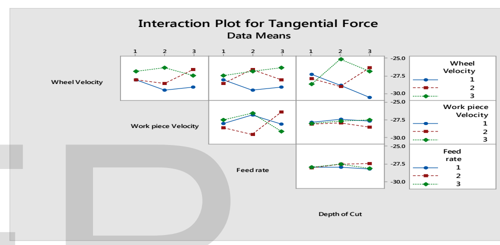
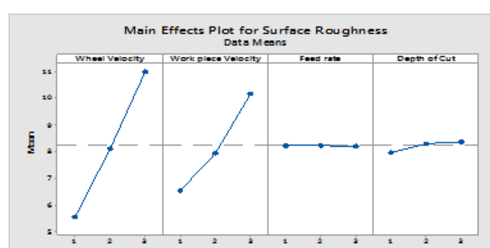


FIGURE.7. THE MAIN EFFECT AND INTERACTION PLOT FOR TANGENTIAL FORCE OF GRINDING OF Al/SiC COMPOSITES

The figure 7 shows the main effect and interaction plot of the tangential grinding force during grinding of Al/SiC composites. The tangential grinding force (F_t) decreases with an increase in the wheel velocity (V_w) and workpiece velocity (V_c). The increase in the wheel velocity and workpiece velocity leads to the thermal softening of the aluminium matrix, which in turn, reduces the tangential grinding force [2]. The increase in the wheel velocity also reduces the maximum chip thickness, which results in a lower grinding force. F_t increases with an increase in the combination of the feed (f) and depth of cut (a_p).



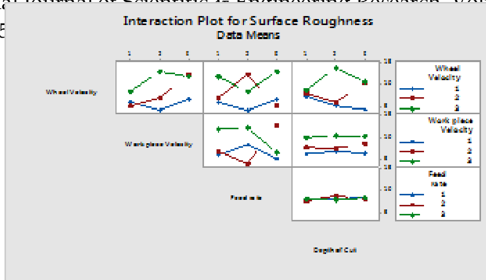


FIGURE. 8. THE MAIN EFFECT AND INTERACTION PLOT FOR SURFACE ROUGHNESS OF GRINDING OF Al/SiC COMPOSITES

The Figure 8 shows the main effect and interaction plot of the surface roughness during grinding of Al/SiC composites. The values of the surface roughness (R_a) decrease with an increase in the wheel velocity (V_w) and workpiece velocity (V_c). This is mainly due to the increase in the relative velocity between the wheel and the workpiece, and the fact that the reduction in contact time reduces the chip thickness, which resulted in a decrease in the R_a values [1]. The surface roughness (R_a) increase with an increase in the combination of feed (f) and depth of cut (a_p). The increase in the combined effect of f and a_p, increases the wheel-work contact area, leading to an increase in grit penetration and the subsequent maximum chip thickness, which invariably increases the R_a values.

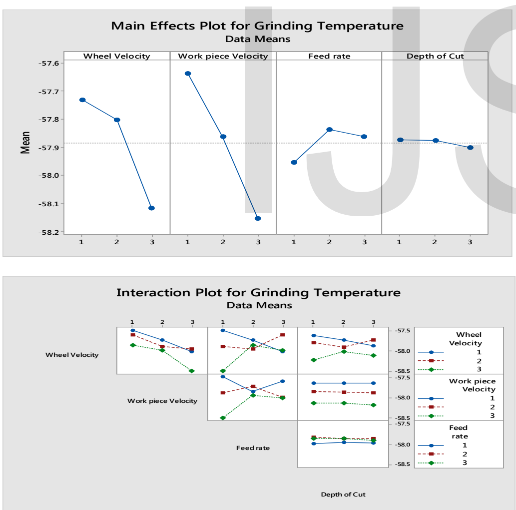


FIGURE. 9. THE MAIN EFFECT AND INTERACTION PLOT FOR GRINDING TEMPERATURE OF GRINDING OF Al/SiC COMPOSITES

The Figure 9 shows the main effect and interaction plot of the grinding temperature during grinding of Al/SiC composites. The grinding temperature (T_g) increases with an increase in the wheel velocity, workpiece velocity, feed and depth of cut. The higher values of the grinding parameters (V_w, V_c, f and d) result in higher grinding temperatures due to the increase of the energy required to grind a unit volume of the material.

4. CONCLUSION

In this study, the Taguchi based L27 orthogonal array was performed to obtain optimum process parameters for the grinding of Al/SiC composites and the conclusions are as follows:

- The optimization results showed that the values of the surface roughness (R_a) decreases with an increase in the wheel velocity (V_w) and workpiece velocity (V_c).
- The tangential grinding force (F_t) decreases with an increase in the wheel velocity (V_w) and workpiece velocity (V_c) and the higher values of the grinding parameters such as wheel velocity (V_w), workpiece velocity (V_c), feed rate and depth of cut result in higher grinding temperature.
- The results indicate that, the wheel velocity (V_w), workpiece velocity (V_c), and feed rate are the main parameters which influence the grinding force, surface roughness and grinding temperature in grinding of Al/SiC composites.
- The best parameters for tangential force and their levels are A3B1C2D2, for surface roughness A3B3C1D3 and for grinding temperature A1B1C2D1
- This method is appropriate and competent to predict the effects of different significant combination of process parameters on the grinding of Al/SiC composites within the levels studied.

REFERENCES

[1] F.H.Sun, X.K.Li, Y.Wang, M.Chen, Studies on the grinding characteristics of SiC particle reinforced aluminium-based MMCs, Key Eng. Mater., 304-305 (2006) 261-265.

[2] Z.W.Zhong, Grinding of aluminium-based metal matrix composites reinforced with
Al2 O3 or SiC particles, Int.J.Adv.Manuf.Technol., 21 (2003) 79-83.

[3] G.Tosun and M.Muratoglu, The drilling of an Al/SiC$_p$ metal matrix composites: Part I: microstructure, Composites Sci. Technol., 64 (2004) 299-308.

[4] I.M.Walton, D.J.Stephenson, and A.Baldwin, The measurement of grinding temperatures at high specific material removal rates, Int. J. Mach. Tools Manuf., 46 (2006), 1617-1625.

[5] Y.M.Quan, and B.Y.Ye, The effect of machining on the surface properties of SiC/Al composites, J. Mater. Process. Technol., 138 (2003), 464-467.

[6] B.Anand Ronald, L.Vijayaraghavan, and R.Krishnamoothy, Studies on the influence of grinding wheel bond material on the grindability of metal matrix composites, Mater. Des.,30 (2009), 679-686.

[7] A. Slowik and J. Slowik, Multi-objective optimization of surface grinding process with the use of evolutionary algorithm with remembered Pareto set, Int. J. Adv. Manuf. Technol , 37 (7-8) (2008), 657-669.

[8] R.Saravanan, P.Asokan and M. Sachidanandam, A multi-objective genetic algorithm (GA) approach for optimization of surface grinding operations, Int. J. Mach. Tools Manuf, 42 (12) (2002), 1327-1334.

[9] Z.W. Zhong, and N.P.Hung, Grinding of alumina/aluminum composites, J. Mater. Process. Technol., 123 (2002), 13-17.

[10] S. Shaji and V. Radhakrishnan, Analysis of process parameters in surface grinding with graphite as lubricant based on the Taguchi method, J. Mater. Process. Technol, 141 (1) (2003), 51–59.

[11] M.Nalbany, H. Gokkaya and G.Sur, " Application of Taguchi method in the optimization of cutting parameters for surface roughness in turning, Mat and Design, Vol. 28, issue 4, pg.1379-1385, 2007.

[12] W.H. Yang and Y.S. Tarng, " Design optimization of cutting parameters for turning operations based on the Taguchi method, J. Mater. Process. Technol, Vol 84, issue 1-3, pg. 122-129, 1997.

[13] Y.F. Chen, Y.J.Lin, Y.C. Lin, S.L. Chen and L.R. Hsu, " optimization of eletro discharge machining parameters on ZrO_2 ceramic using the Taguchi method, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture February 1, 2010 vol. 224 no. 2 195-205.

[14] DC Montgomery, Design and analysis of experiments. Wiley, New York, 2001.