Effect of Tool Geometry on Dimensional Accuracy and Surface Finish of Turned Parts

M. N. Islam[1,a], B. G. M. Gharh[2,b], and A. Pramanik[1,c]

[1]Department of Mechanical Engineering, Curtin University, Australia

[2]School of Engineering, Edith Cowan University, Australia

[a]M.N.Islam@curtin.edu.au, [b]bgharh@our.ecu.edu.au, [c]alokesh.pramanik@curtin.edu.au

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Abstract. This paper investigates, experimentally and analytically, the influence of tool geometry on two major dimensional accuracy characteristics of a turned part—diameter error and circularity—and the surface finish characteristic arithmetic average. Data were analysed via two methods: Pareto ANOVA and Taguchi method. The findings indicate that the two selected tool geometry parameters—insert shape and nose radius—have a considerable effect on diameter error (total contribution 67.0%) and minor effects on surface finish (total contribution 11.6%) and circularity (total contribution 7.5%). The major contributor to surface finish is feed rate, whereas circularity is dominated by interaction effects.

Introduction

Machining operations are influenced by several input variables, of which cutting tool is the most critical one [1]. The cutting tool affects almost all aspects of machining, such as chip formation, heat generation, tool wear, dimensional accuracy, and surface finish. The influence of the cutting tool, especially its geometry, on the dimensional accuracy and surface finish of machined parts is more obvious, as the final shape, dimensions, finish, and special geometric details are created by direct contact between the cutting tool and the workpiece. Research on cutting tools concentrates on its two major aspects: material and geometry. This paper is limited to a study on the influence of tool geometry.

Investigations of the effect of tool geometry on machining operation have received notable attention in the literature. However, these studies primarily focus on machinability characteristics such as cutting force [2,3], residual stress [4,5], chip formation [6,7], heat generation [8,9], and tool wear [10,11]. A review of the effect of tool geometry on finish turning can be found in Dorga et al. [12]. A number of papers [13-15] have reported on dimensional accuracy and surface finish, but they typically considered the effect of major cutting parameters—cutting speed, feed rate, and depth of cut. It appears that there is a lack of research on the effect of tool geometry on technical characteristics, such as dimensional accuracy and surface finish of finished component parts. The objective of this research is to fill this gap.

Scope

Single-point cutting tools used in turning operations are available in three major types: (a) solid tool, (b) brazed insert, and (c) mechanically clamped insert. The mechanically clamped type insert tool is the most popular choice and is the topic of our investigation. Tool inserts are available in a number of shapes, such as triangle, square, diamond, and round. The strength of the cutting edge of an insert depends on its shape. The larger the included angle, the higher the strength of the edge; however, it requires more power and has a higher tendency for vibration [16]. Therefore, it is anticipated that the shape of the insert might influence the dimensional accuracy and surface finish of the finished part, and it was selected as an input variable in this study. Insert nose radius is another variable know to influence surface finish, chip breaking, and insert strength. As such, it was also selected as an input variable. The third selected input variable is feed rate, which is known to have a great influence on surface roughness.

The two most important dimensional accuracy characteristics of turned component parts are diameter error and circularity, and they were selected for the present study. Surface finish can be expressed through a number of parameters, such as the arithmetic average, root-mean-square roughness, peak-to-valley height, and ten-point height. The arithmetic average is the most commonly used roughness parameter because of its simplicity. In this study, arithmetic average was adopted to represent surface roughness.

The results were analysed applying two techniques—Pareto analysis of variation (ANOVA), and Taguchi's signal-to-noise (S/N) ratio analysis. Pareto ANOVA is an excellent tool for determining the contribution of each input parameter and its interactions on the output parameters. It is a simplified ANOVA analysis method that does not require an ANOVA table and does not use *F*-tests. Therefore, it does not require detailed knowledge about the ANOVA method. Further details on Pareto ANOVA are available in Park [17]. The Taguchi method is another popular tool for parameter design. It applies signal-to-noise (S/N) ratio as a quantitative analysis tool for optimizing the outcome of a manufacturing process. The S/N ratio can be calculated using the following formula [18]:

$$S/N = -10\log\frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

where n is the number of observations and y is the observed data.

The above formula is suitable for quality characteristics in which the adage 'the smaller the better' holds true. All three quality characteristics considered fall in this category. The higher the value of the S/N ratio, the better the result is, because it guarantees the highest quality with minimum variance. A thorough treatment of the Taguchi method can be found in Ross [18].

Experimental Work

The experiments were planned using Taguchi's orthogonal array; a three-level, three-parameter L_{27} orthogonal array was selected for our experiments. A copy of L_{27} (3^{13}) array is available in Taguchi [19]. The details of the input parameters are given in Table 1. A total of 27 experimental runs were conducted; they were carried out in nine parts, each of which was divided into three segments. Each part was turned with a new insert, shape, and nose radius, which were determined by the design of experiment (DoE). The inserts used were manufactured by Stellram (USA).

AISI-4340 steel was chosen as the work material, as it is readily available and widely used in the industry. The nominal size of each part was 170 mm length and 40 mm diameter. The experiment was carried out on a Harrison conventional lathe, with 330 mm swing, under dry condition. The depth of cut (1 mm) and cutting speed (212 m/min) were maintained constant. The diameter error and circularity were measured by a Discovery Model D-8 coordinate measuring machine (CMM), manufactured by Sheffield (UK). The surface roughness parameter, arithmetic average (R_a), for each turned surface was measured with a Surftest SJ-201P, manufactured by Mitutoyo (Japan).

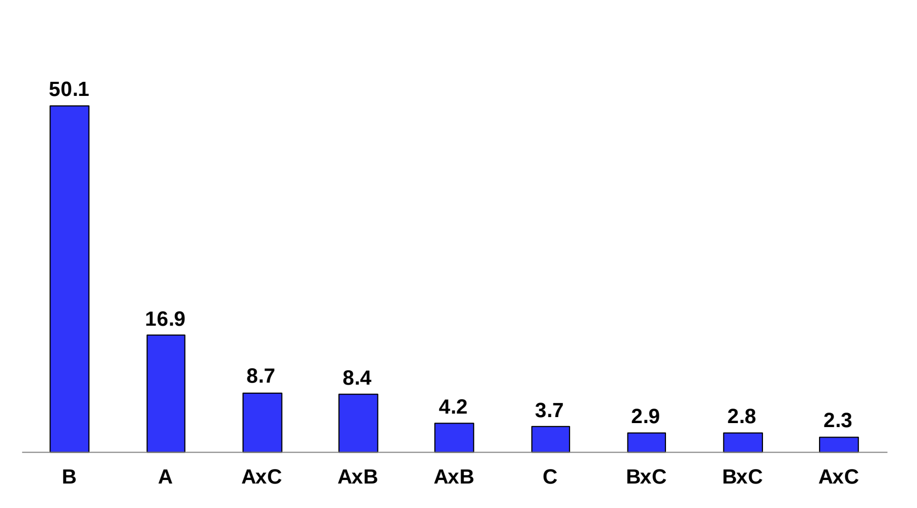
Table 1. Input variables

Input parameters	Unit	Symbol	Levels		
			Level 0	Level 1	Level 2
Insert shape		A	 Square	 Diamond	 Triangle
Nose radius	mm	B	0.4	0.8	1.2
Feed rate	mm/rev	C	0.11	0.22	0.33

Results and Analysis

Diameter Error. The Pareto ANOVA analysis for diameter error is given in Table 2. It shows that nose radius (B) has the most significant effect on diameter error, with a contribution ratio P ≅ 50%, followed by insert shape (A) (P ≅ 16%). The interactions between insert shape and feed rate (A×C) and between insert shape and nose radius (A×B) also played roles, with a contribution of 8.7% and 8.4%, respectively. Feed rate (C) showed a small effect (P ≅ 4%). It is worth pointing out that the total contribution of the main effects was about 71%, compared to the total contribution of the interaction effects of 29%. As such, it is moderately difficult to optimize diameter error by selecting input parameters.

Table 2. Pareto ANOVA analysis of diameter error

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	106.07	121.05	118.39	110.64	119.08	115.09	121.93	119.18	112.56
1	118.32	99.17	108.71	117.95	115.99	118.71	114.28	114.73	114.57
2	121.99	126.16	119.28	117.79	111.31	112.58	110.17	112.47	119.24
Sum of squares of difference (S)	416.89	1233.05	206.25	104.38	91.71	56.96	213.76	70.01	70.46
Contribution ratio (%)	16.92	50.05	8.37	4.24	3.72	2.31	8.68	2.84	2.86
									
Cumulative contribution	50.05	66.97	75.65	84.02	88.26	91.98	94.84	97.68	100.00
Check on significant interaction		AxC two-way table (not included)							
Optimum combination of significant factor level		A2B2C0							

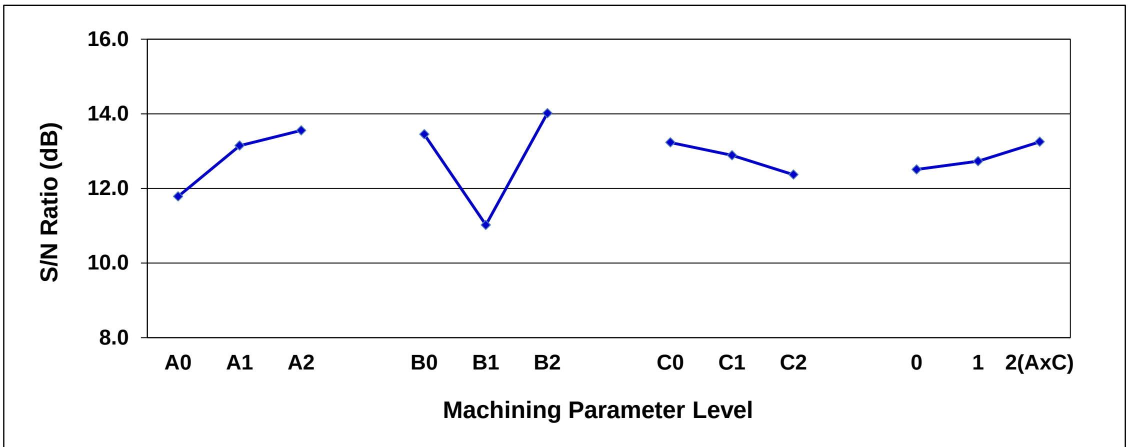


Fig. 1 Response graph for diameter error

The response graph for the mean S/N ratio is shown in Fig. 1. The results show that parameter B (nose radius) has the most significant effect on diameter error. Fig. 1 also shows that as the included angle increases, the diameter error increases, and the worst diameter error is achieved by the square-shaped insert, which has a 90º included angle. The most likely cause is the more elastic deformation of the workpiece, caused by increased cutting force due to the increase in the included angle.

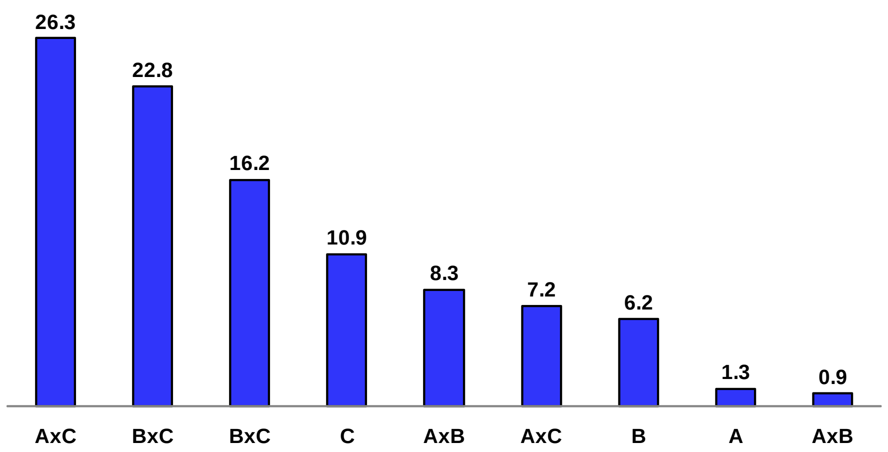
In selecting the optimum combination of parameters, both the Pareto ANOVA analysis (Table 2) and the response for the mean S/N ratio (Fig. 1) confirm that the largest nose radius (B2) provides the lowest diameter error. A two-way table of A×C interactions showed that A2C0 achieved the lowest diameter error; i.e., triangular-shaped insert and lowest feed rate (0.11 mm/rev). The two-way table is not included in this paper due to space constraints. The best combination is A2B2C0.

Circularity. The Pareto ANOVA analysis for circularity is given in Table 3. It shows that among the input variables, feed rate (C) has the most significant effect on circularity, with a contribution ratio P ≅ 11%, followed by nose radius (B) (P ≅ 6%) and insert shape (A) (P ≅ 1%). In this Pareto graph, the dominance of the interaction effects is noteworthy. The interaction between insert shape and feed rate (A×C) has the highest influence (P ≅ 26%), followed by interaction of nose radius and feed rate (B×C) (P ≅ 23%). The total contribution of the interaction effects is about 82%, compared to the total contribution of the main effects of 18%, thus making it highly difficult to optimise the circularity error by selecting the input parameters.

The response graph for the mean S/N ratio for circularity is shown in Fig. 2. The best circularity can be achieved by the A1B1C1 combination; i.e., turning with a diamond-shaped insert with medium nose radius (0.8 mm), at a medium feed rate (0.22 mm/rev).

Table 3. Pareto ANOVA analysis of circularity

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	377.07	389.14	388.21	389.89	393.01	385.52	400.99	387.22	359.86
1	389.55	394.21	385.10	395.92	395.74	397.76	399.67	355.32	404.76
2	384.55	367.81	377.86	365.35	362.41	367.89	350.51	408.62	386.54
Sum of squares of difference (S)	236.43	1177.45	169.23	1573.68	2054.87	1353.24	4967.88	4316.72	3059.81
Contribution ratio (%)	1.25	6.23	0.89	8.32	10.87	7.16	26.27	22.83	16.18



Cumulative contribution	26.27	49.10	65.28	76.15	84.47	91.63	97.86	99.11	100.00
Check on significant interaction	AxC two-way table (not included)								
Optimum combination of significant factor level	A1B1C1								

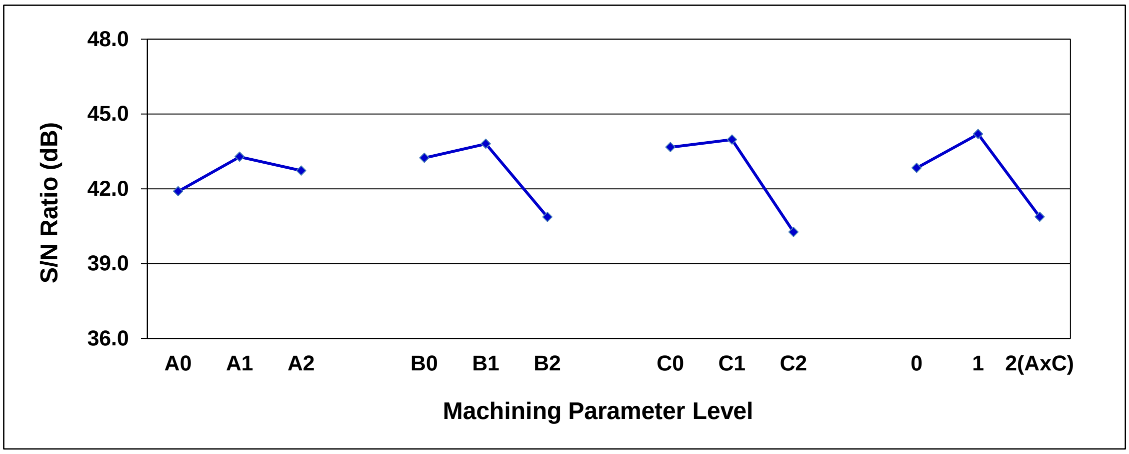
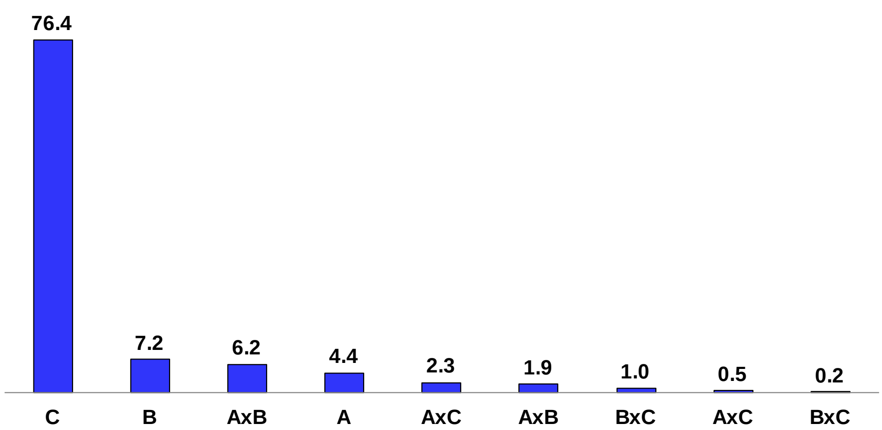


Fig. 2 Response graph for circularity

Surface Roughness. The Pareto ANOVA analysis for surface roughness is given in Table 3. It shows that feed (C) has the most significant effect on surface (P ≅ 76%), followed by nose radius (B) (P ≅ 7%). The interactions between insert shape and nose radius (A×B) also played a role, with a contributing ratio of P ≅ 6%. Insert shape (A) showed a small effect (P ≅ 4%). In this case, the high influence of feed rate (C) is noteworthy. The total contribution of the main effects is about 88%, compared to the total contribution of the interaction effects of 12%. Therefore, it is relatively easy to optimize the surface finish by selecting the input parameters, especially through proper selection of feed rate.

Table 4. Pareto ANOVA analysis of surface roughness

Sum at factor level	Factor and interaction								
	A	B	AxB	AxB	C	AxC	AxC	BxC	BxC
0	-25.69	-70.38	-33.10	-21.41	31.70	-51.32	-59.00	-54.07	-45.93
1	-60.79	-35.02	-44.21	-62.62	-49.57	-41.89	-39.36	-39.62	-40.71
2	-47.03	-28.10	-56.20	-49.47	-115.65	-40.29	-35.14	-39.82	-46.87
Sum of squares of difference (S)	1876.56	3085.53	801.30	2658.61	32683.30	213.12	972.54	411.58	66.18
Contribution ratio (%)	4.39	7.21	1.87	6.22	76.42	0.50	2.27	0.96	0.15



Cumulative contribution	76.42	83.63	89.85	94.24	96.51	98.38	99.34	99.84	100.00
Check on significant interaction	AxB two-way table (not included)								
Optimum combination of significant factor level	A0B2C0								

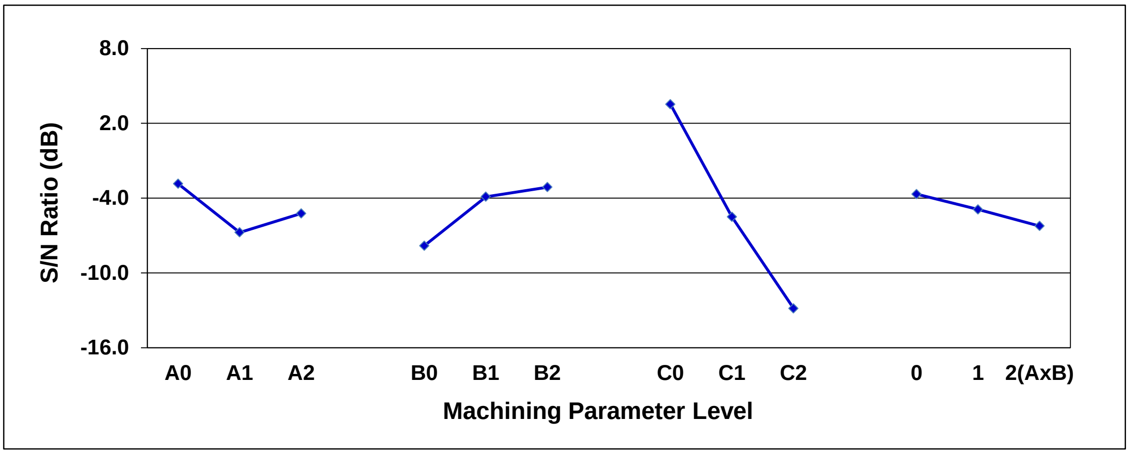


Fig. 3 Response graph for surface roughness

The results obtained from the Pareto ANOVA analysis, shown in Table 4, are verified by the response graph for the mean S/N ratio, shown in Fig. 3. The results show that parameter C (feed rate) has the most significant effect on surface roughness, represented by the highest slope on the response graph. The findings shown in Fig. 3 support the results obtained from the Pareto ANOVA analysis, shown in Table 2.

In selecting the optimum combination of parameters, both the Pareto ANOVA analysis (Table 4) and the response for the mean S/N ratio (Fig. 3) confirm that the lowest feed rate (C0) provides the best surface finish. A two-way table of A×B interactions showed that A0B2 achieved the best surface roughness; i.e., diamond-shaped insert and largest nose radius (1.2 mm). The two-way table is not included in this paper due to space constraints. The best surface roughness can be achieved by the A0B2C0 combination. The influence of feed rate and nose radius on surface roughness is well known, and most of the geometric models for surface roughness include these two parameters. As expected, surface roughness improved as nose radius increased, and deteriorated as feed rate increased.

Summary

From the experimental work conducted and the subsequent analysis, the following conclusions can be drawn:

- Tool geometry parameters—insert shape and nose radius—have considerable effects on diameter error (total contribution 67.0%). The effect of feed rate is minor (contribution 3.7%).
- No single parameter contributes significantly to circularity, and the interaction effected is dominant (total contribution 71.6%).
- Surface roughness is mainly affected by feed rate (contribution 76%). Tool nose radius has a minor effect (contribution 7%).

References

[1] T. Drozda, C. Wick (Eds.), Tool and Manufacturing Engineers Handbook: Machining, Society of Manufacturing Engineers, Dearborn, 1983.

[2] L. Qian, M.R. Hossan. Effect on cutting force in turning hardened tool steels with cubic boron nitride inserts. J. Mat. Proc. Tech., 191 (2007) 274-278.

[3] M. Gunay, E. Aslan, I. Korkut, U. Seker, Investigation of the effect of rake angle on main cutting force, Int. Int. J. Machine Tools & Manuf., 44 (2004) 953-959.

[4] J.D. Thiele, S.N. Melkote, Effect of cutting edge geometry and workpiece hardness on surface generation in the finish hard turning of AISI 52100 steel J. Mat. Proc. Tech., 94 (1999) 216-226.

[5] M. Liu, J. Takagi, A. Tsukuda, Effect of tool nose radius and tool wear on residual stress distribution in hard turning of bearing steel, J. Mat. Proc. Tech., 150 (2004) 234-241.
[6] E. Usui, A. Hirota, Analytical prediction of three dimensional cutting process—Part 2: Chip formation and cutting force with conventional single-point tool, J. Eng. for Industry 100 (1978): 229.
[7] S-P. Lo, An analysis of cutting under different rake angles using the finite element method, J. Mat. Proc. Tech., 105 (2000) 143-151.
[8] T. Özel and E. Zeren, Finite Element Analysis of the influence of edge roundness on the stress and temperature fields induced by high speed machining, Int. J. Adv. Manuf. Tech., 35 (2007) 255-267.
[9] H.Saglam, F. Unsacar, S. Yaldiz, Investigation of the effect of rake angle and approaching angle on main cutting force and tool tip temperature, Int. J. Machine Tools & Manuf., 46 (2006): 132-41.
[10] K.C. Ee, P.X. Li, A.K. Balaji, I.S. Jawahir, R. Stevenson, Performance-based predictive models and optimization methods for turning operations and applications: Part 1- Toolwear/tool life in turning with coated groove tools, J. Manuf. Proc., 8 (2006) 54-66.
[11] J.I. Hughes, A.R. Sharman, C. Ridgwayk, The effect of cutting tool material and edge geometry on tool life and workpiece surface integrity, Proc. Inst. of Mech. Engineers, Part B, J. of Eng. Manuf., 220 (2006) 93-107.
[12] M. Dorga, V.S. Sharma, J. Dureja, Effect of tool geometry variation on finish turning - A review, Eng. Sci. and Tech. Review, 4 (2011) 1-13.
[13] M.Marcos-Bárcena, M.A. Sebastián-Pérez, J.P. Contreras-Samper, M. Sánchez-Carrilero, M. Sánchez-López, J.M. Sánchez-Sola, Study of roundness on cylindrical bars turned of aluminium-copper alloys UNS A92024, J. Mat. Proc. Techn. 162-163 (2005): 644-648.
[14] C.J. Tzeng, Y.H. Lin, Y.R. Yang, M.C. Jeng, Optimization of turning operations with multiple performance characteristics using the Taguchi method and Grey relational analysis, J. Mat. Proc. Tech., 209 (2009): 2753-2759.
[15] N.H. Rafi, M.N. Islam, An investigation into dimensional accuracy and surface finish achievable in dry turning, Machin. Sci. and Tech., 13 (2009) 571-589.
[16] S. Kalpajian, S.R. Schmid, Manufacturing Engineering and Technology, sixth ed., Pearson Education Inc., New Jersty, 2010.
[17] S.H. Park, Robust Design and Analysis for Quality Engineering, Chapman & Hall, London, 1996.
[18] P.J. Ross, Taguchi Techniques for Quality Engineering, McGraw-Hill, New York, 1988.
[19] G. Taguchi, System of Experimental Design: Engineering Methods to Optimize Quality and Minimize Cost, Vol. 2, UNIPUB/Kraus Int. Pub., White Plains, NY, 1987.