Application of Taguchi's Orthogonal Array and Overall Evaluation Criteria in Turning of AISI D2 Steel in Dry and Forced Air-Cooled Environment

S. K. Rajbongshi and D. K. Sarma

Abstract Optimization of process parameters is an important technique in machining sector. In the present work, an experimental study has been performed in turning of AISI D2 steel using coated carbide tool in dry and forced air-cooled environment. Taguchi's orthogonal array L_9 has been used for running the experiments considering cutting speed, feed rate and depth of cut as process parameters and surface roughness, flank wear and cutting force as performance parameters. To optimize the performance parameters together in a single setting, an overall evaluation criterion (OEC) has been used. Analysis of variance (ANOVA) and average performance value of OEC is also analyzed. It is found that from the predicted setting of the average performance value of OEC, the surface roughness, flank wear and cutting force is reduced in both dry turning (DT) and forced air-cooled turning (ACT) as compared to the optimum value obtained from the experimental run.

Keywords Taguchi's overall evaluation criteria · Dry turning · Air-cooled turning

1 Introduction

The machining operation is an important area in manufacturing sector. In order to manufacture products at competitive price, selection of proper cutting tool as well as process parameter is an important aspect. The process parameter setting plays an important role in obtaining optimum values of performance parameters. The hard machining operations can provide equivalent surface finish with grinding and better complex parts in less time and cost as compared to grinding operations. The researchers have focused mainly on machining of hard materials using coated carbide, ceramics and CBN inserts, mentioned by Bartarya and Choudhury [1]. Shao et al. mentioned the machinability of stellite 12 alloys with the application of coated and uncoated carbide tools in dry environment [2]. They suggested that the coated carbide tool was better as compared to uncoated carbide tool in minimizing flank

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wear. Strenkowski et al. used CBN and advanced ceramic cutting tool materials in machining hardened steel [3]. The different wear behaviors of CBN tool was studied by Chou et al. in machining of hardened AISI 52100 steel [4]. The authors reported that the performance of low CBN content tool was better in terms of surface roughness and flank wear as compared to high CBN content tool. The machinability of AISI 4340 steel and AISI D2 steel using coated carbide tool and mixed alumina insert, respectively, were studied by Lima et al. [5]. It was reported that machining of AISI D2 steel using mixed alumina inserts gave equivalent surface finish comparable to cylindrical grinding.

In machining, due to the high friction between the tool and work piece generates high strain rates. Due to this temperature, generation is high at the tool work piece junction. Generally, liquid coolants are applied at the tool work piece junction to minimize the heat as well as for lubrication purposes. Dry machining is an important aspect considering it to be environmentally friendly. Klocke and Eisenblatte worked on dry machining; Weinert et al. mentioned the concept of near-dry machining (NDM) [6, 7]. Dixit et al. mentioned the green manufacturing concepts and its application in manufacturing area [8]. Now a day, the use of forced air-cooling is a new alternative to avoid the use of harmful coolants in machining. Sarma and Dixit studied the application of compressed air in machining of grey cast iron with mixed oxide ceramic tool [9]. Air-cooled turning was found to be better in terms of machining performances than dry turning. Similar observation was mentioned by Liu et al. [10].

The use of statistical analysis is an important tool in machining sector. The statistical tool helps in modeling and optimizing the machining parameters. Among the different statistical tool, Taguchi's optimization technique is widely used by the researchers. It helps the experimenters to give an optimal solution with less number of experiments. Panda et al. used Taguchi's L_9 orthogonal array in hard turning of EN 31 steel using multilayer coated carbide inserts [11]. The authors observed feed and depth of cut as the significant parameters. Das et al. found minimum tool wear using Taguchi's L_9 orthogonal array in machining AISI D2 steel with coated carbide inserts at a cutting speed of 150 m/min, feed 0.25 mm/rev and depth of cut 0.5 mm [12]. Singh and Kumar used Taguchi's orthogonal array to reduce tool wear in machining EN 24 steel with coated carbide inserts [13].

From the above literature reviews, it has been observed that the researchers are mainly using ceramic and CBN tool in machining hard materials, although few researchers have used coated carbide tool. Due to the high cost of ceramic and CBN tool, in the present work, an effort has been made using coated carbide tool in machining of hardened AISI D2 steel to obtain the best results similar to ceramic and CBN. Also, very few works have been done in turning operation using forced compressed air as the medium of operation. So, in this present work forced compressed air is used as the medium of operation. For comparison, dry turning is also performed. It is also found that lot of researchers are using Taguchi's single response optimization technique in optimizing machining parameters. But multi-response optimization technique such as overall evaluation criteria (OEC) application is very limited in machining area. With this regard, in this work OEC criterion is being applied in turning of hardened AISI D2 steel with coated carbide tool in dry and forced air-cooled environment.

2 Experimental Set Up

The equipments which are used for conducting the experiments are as follows:

(i) For the turning operation, high-speed conventional lathe of Make: Tussor Machine Tools India Pvt. Ltd. & Model: SC250 is used. The motor power of the lathe is 5.5 kW and spindle speed is 40–2300 rpm.
(ii) Surface roughness is measured using surface roughness tester of Make: Taylor Hobson & Model: S-128 is used. The gauge range is 0–400 μm and sampling length are 0.25–8 mm.
(iii) For tool flank measurement, optical microscope of Make: Olympus & Model: BX51 M is used. The magnification range is 50X–1000X.
(iv) For measurement of cutting forces, lathe tool dynamometer of Make: Kistler & Model: 9257 B is used. The range of the cutting force is 0–10 KN.
(v) Reciprocating compressed air of Make: Elgi & Model: TS03HN is used for generating compressed air. The power of the compressor is 3 HP and maximum pressure limit is 12 kg/cm^2. Compressor air flow rate and pressure at the nozzle end are 0.00041 m^3/s and 1.052 bar, respectively.
(vi) The work piece is heat-treated up to 48 HRC in an electric muffle furnace of Make: Voltam furnace Industries. The temperature of the furnace is 1400 °C with digital PID controller.

Figure 1 shows the experimental set up along with the specimen (work piece).

3 Results and Discussions

In this section, the results obtained from turning AISI D2 steel (48 HRC) with coated carbide tool in dry and forced air-cooled environment are discussed. The experimental design, Taguchi's overall evaluation criteria (OEC), analysis of variance (ANOVA) and average performance values of OEC are analyzed in this section.

3.1 Experimental Design

In the present work, three process parameters viz. cutting speed, feed and depth of cut have been considered for the study. Each parameter has three levels. The performance parameters considered for the study are surface roughness (SR), flank wear (FW) and

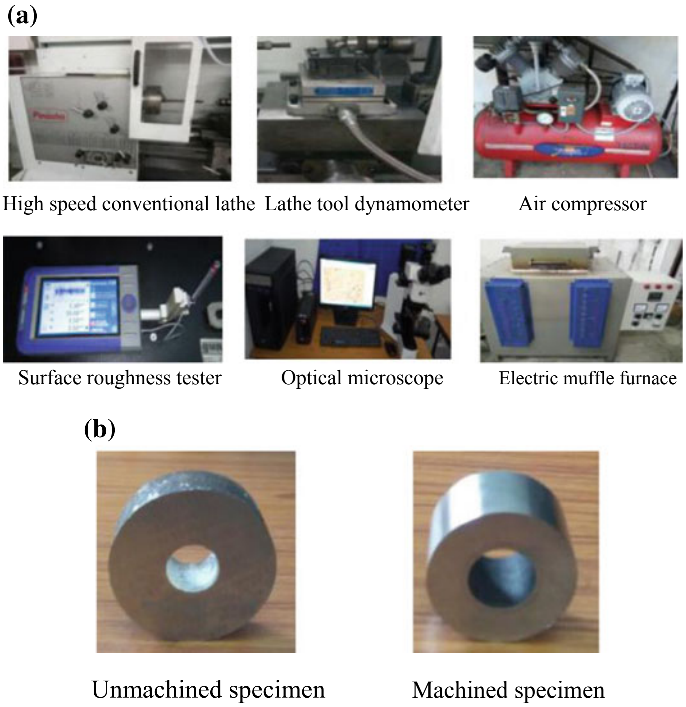

Fig. 1 **a** Experimental set up. **b** Unmachined and machined specimen

cutting force (CF). The degree of freedom (DOF) of each parameter is 2. The total DOF for all the three parameters including the average is 7. Therefore, Taguchi's orthogonal array (OA) L_9 has been considered for the experimental design without considering the interaction effect. Table 1 shows the process parameters along with their levels and DOF.

Table 1 Process parameters along with their levels and DOF

Parameters	Level			DOF
	1 (Low)	2 (Medium)	3 (High)	
v (m/min)	100	125	150	2
f (mm/rev)	0.05	0.10	0.15	2
d (mm)	0.25	0.40	0.55	2

3.2 Overall Evaluation Criteria (OEC)

Taguchi's OA method, a fractional factorial design is useful in the sense that it selects particular settings of the parameters and gives the optimum value of the responses within that particular setting. This saves the time and cost of the experimenters without doing the full factorial design. In general, Taguchi's optimization method is applied to optimize single response at a time. This takes a lot of time and cost to optimize several responses separately. To overcome this problem, overall evaluation criteria (OEC) can be used to optimize the multiple responses obtained from Taguchi's OA table in one particular setting. This helps the experimenter to run only one confirmation experiment for the particular setting and to get the optimum value of the multi responses. In multi-objective optimization problems each response has different units, measurements, quality characteristics, and relative weight. To combine these different characteristics and criteria, the response values must be weighted and normalized accordingly. The formula for finding OEC is given as follows:

$$\begin{aligned} \mathrm{OEC}_j = {} & [(S_{j1-}W_1)/(B_1 - W_1) \times R_1] + [(S_{j2-}W_2)/(B_2 - W_2) \times R_2] \\ & + [(S_{j3-}W_3)/(B_3 - W_3) \times R_3] \end{aligned} \tag{1}$$

Here, W represents worst value and B represents best value of a response, R represents relative weight of response, S means sample value, $j = 1, 2, 3, \ldots, 9$ in this experimental run. The indexes 1, 2, and 3 represent for surface roughness, flank wear and cutting force, respectively. The experimental run settings having higher OEC values give the optimum response values. Table 2 shows the Taguchi's OA L_9 along with its response values and corresponding OEC values calculated using Eq. 1 in dry turning (DT) and air-cooled turning (ACT), respectively. The data for ACT is taken from author's previous work [14]. Here the values of R_1, $R_{2,}$ and R_3 are taken as 40%, 40%, and 20%, respectively, for surface roughness, flank wear and cutting force considering the importance of responses.

3.3 Analysis of Variance (ANOVA)

ANOVA is a statistical analysis tool used for checking the influence of parameters in an experiment. In the present work, ANOVA is carried out for multi-objective optimization technique of OEC in DT and ACT. Tables 3 and 4 show the ANOVA for OEC in DT and ACT, respectively. From Table 3, it is observed that depth of cut and cutting speed are the most influential parameters for OEC as they have higher percentage contribution in OEC. Between depth of cut and cutting speed, depth of cut is found to be more significant as compared to the cutting speed because depth of cut has higher percentage contribution as compared to cutting speed in terms of OEC in DT. Feed has less influence for OEC in DT. Similarly from Table 4, cutting speed and depth of cut are the most significant parameters for OEC in ACT. Between

Table 2 Taguchi's OA L_9 along with its response values and OEC in DT and ACT

Expt.	v	f	d	SR (μm)		FW (mm)		CF(N)		OEC	
No.	(m/min)	(mm/rev)	(mm)	DT	ACT	DT	ACT	DT	ACT	DT	ACT
1	100	0.05	0.25	1.44	1.77	0.15	0.10	113	48	71.36	78.42
2	100	0.10	0.40	1.38	1.61	0.22	0.19	176	235	61.68	59.94
3	100	0.15	0.55	1.33	1.53	0.43	0.27	202	299	35.55	48.38
4	125	0.05	0.55	1.36	1.57	0.40	0.29	182	163	38.11	54.45
5	125	0.10	0.25	1.30	1.36	0.23	0.18	102	99	82.17	85.26
6	125	0.15	0.40	1.33	1.64	0.35	0.28	189	182	48.75	50.58
7	150	0.05	0.40	1.30	1.42	0.35	0.30	102	79	65.03	67.70
8	150	0.10	0.55	1.55	1.93	0.40	0.40	178	225	10.51	15.89
9	150	0.15	0.25	1.57	2.12	0.38	0.30	55	96	27.14	29.50

Table 3 ANOVA table for OEC in DT

Parameters	DOF	Sum of square (SS)	Mean sum of square (SS)	*F*-ratio	% Contribution
v	2	971.85	485.92	0.88	22.71
f	2	241.59	120.80	0.22	5.64
d	2	1963.69	981.84	1.79	45.91
Error (e)	2	1099.67	549.83		25.74
Total	8	4276.80			100

Table 4 ANOVA table for OEC in ACT

Parameters	DOF	Sum of square (SS)	Mean sum of square	*F*-ratio	% Contribution
v	2	1266.31	663.15	1.76	32.55
f	2	869.25	434.62	1.21	22.34
d	2	1034.27	517.13	1.43	26.58
Error (e)	2	720.89	360.45		18.53
Total	8	3890.72			100

cutting speed and depth of cut, cutting speed is found to be more significant due to higher percentage contribution of cutting speed as compared to depth of cut for OEC in ACT. Feed has less influence as compared to cutting speed and depth of cut for OEC in ACT.

3.4 Average Performance Value of OEC

The average performance values are found out to evaluate the optimal process parameter combination to obtain the optimum response value (OEC). At first, OEC is found out for each experimental run for all the responses. Then OEC values are calculated based on the levels. The higher values of OEC for a particular parameter setting give the optimum value. Tables 5 and 6 show the average performance value with their optimal settings for OEC in DT and ACT, respectively. The bold letter indicates the optimum setting of the parameter value. From both Tables 5 and 6, the optimal

Table 5 Average performance value and optimal parameter combination for OEC in DT

Parameter	Level		
	1	2	3
v (m/min)	56.19	**56.34**	34.22
f (mm/rev)	**58.17**	51.45	37.14
d (mm)	**60.22**	58.48	28.05

Table 6 Average performance value and optimal parameter combination for OEC in ACT

Parameter	Level		
	1	2	3
v (m/min)	62.24	**63.43**	37.69
f (mm/rev)	**66.86**	53.70	42.82
d (mm)	**64.39**	59.40	39.58

setting of the parameter for OEC in DT and ACT is v_2-f_1-d_1, i.e., $v = 125$ m/min, $f = 0.05$ mm/rev, $d = 0.25$ mm.

3.5 Comparison of Optimum Value of OEC from Experimental Run and Level Wise Optimum Parametric Average Performance Value of OEC

It is observed that the Expt. No. 5 has higher value of OEC for both DT and ACT, i.e., the setting is v_2-f_2-d_1 from Table 2. The optimum value of average performance for OEC is found as v_2-f_1-d_1 that represents in Tables 5 and 6. The confirmatory experiment for both these optimal settings of OEC is performed. The values of surface roughness, flank wear and cutting force using the predicted performance value of OEC are shown in Table 7 along with the comparison of optimal values from Expt. no 5 for both DT and ACT. Using the Taguchi's OEC criteria and the average performance value, it is observed that the surface roughness, flank wear and cutting force is improved by 5.38%, 4.34%, and 22.54%, respectively, for DT. Similarly for ACT, surface roughness, flank wear and cutting force is improved by 4.41%, 16.67%, and 15.15%, respectively. From these results, it is found that the average performance value of OEC is higher in case of ACT as compared to that of DT which implies that ACT is better as compared to DT. From the comparison of

Table 7 Comparison of experimental values of optimal experimental run and optimal average performance value of OEC in DT and ACT

Optimal machining parameters				
Condition	DT		ACT	
	Using optimal value in expt. no 5 from L_9 table	Using optimal average performance prediction value	Using optimal value in expt. no 5 from L_9 table	Using optimal average performance prediction value
Level	v_2-f_2-d_1	v_2-f_1-d_1	v_2-f_2-d_1	v_2-f_1-d_1
SR (μm)	1.30	1.23	1.36	1.30
FW (mm)	0.23	0.22	0.18	0.15
CF (N)	102	79	99	84

OEC value, it is observed that in ACT, the improvement rate of tool wear is better as compared to DT. But the improvement rate of surface roughness and cutting force is better in case of DT than ACT.

4 Conclusion

In this work, Taguchi's OA L_9 has been used for conducting the experiments in turning of AISI D2 steel using coated carbide tool in a dry and forced air-cooled environment. OEC technique is used for optimization of surface roughness, flank wear and cutting force at a single setting for both DT and ACT. The result obtained from Taguchi's analysis in both DT and ACT is summarized as follows:

1) From ANOVA, the depth of cut followed by cutting speed is the most influential parameter in terms of multi-optimization criteria in DT, whereas cutting speed followed by depth of cut are the most influential parameters in ACT. In both DT and ACT, feed rate has less significance for OEC.
2) The optimal experimental run has been found using higher OEC criteria which is found in experiment number 5 for both DT and ACT.
3) The optimal experimental run is compared with the optimal settings of the average performance value of OEC for both DT and ACT. There is an improvement of 5.38, 4.34, and 22.54% for surface roughness, flank wear and cutting force in DT using the optimal setting of average performance value in comparison to the experimental run 5. Similarly, for ACT; surface roughness, flank wear and cutting force is improved by 4.41%, 16.67%, and 15.15%, respectively.
4) From OEC, the improvement rate of tool wear is better in case of ACT than DT, but the improvement rate for surface roughness and cutting force is better in DT as compared to ACT.

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