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OPTIMIZATION OF SURFACE ROUGHNESS IN FINISH MILLING OF AISI P20+S PLASTIC-MOLD STEEL

OPTIMIZACIJA HRAPAVOSTI POVRŠINE MED KONČNO MEHANSKO OBDELAVO JEKLA ZA BRIZGANJE PLASTIKE TIPA AISI P20+S

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In this study, the performance of the cutting parameters used in the finish milling of the AISI P20+S plastic-mold steel were researched and the optimum machining conditions were identified. Experiments were made according to the Taguchi L_8 ($4^1 \times 2^3$) orthogonal array. The evaluation of the experimental results was based on the signal/noise (*S/N*) ratio. Control factors for the optimum surface-roughness values were determined using the Taguchi method. Four different cutting speeds (100, 150, 200, 250) m/min, two different feed rates (0.1, 0.2) mm/r, depths of cut (0.12, 0.16) mm and cooling methods (dry and wet) were selected as the control factors. The effects of the control factors on the surface roughness were determined with an analysis of variance (ANOVA) using the experimental results. A multiple regression analysis was also conducted using the experimental results. A higher correlation coefficient (R^2) was obtained with a linear regression model, which showed a value of 0.923 for R_a. Finally, confirmation tests were performed and they showed that the optimization was successfully implemented. Using the Taguchi analysis, we found the optimum results for the surface roughness at a cutting speed of 150 m/min, a feed rate of 0.1 mm/r, a depth of cut of 0.16 mm and the wet cooling method. The results of the calculation and confirmation tests for the R_a were 0.288 µm and 0.296 µm.

Keywords: AISI P20+S, finish milling, Taguchi method, surface roughness

V študiji avtor raziskuje in analizira učinek uporabljenih parametrov rezanja na končno mehansko obdelavo z rezkanjem jekla za brizganje plastike tip AISI P20+S. Z analizo je ugotovil tudi optimalne pogoje mehanske obdelave. Preizkuse je izvedel v skladu s Taguchijevo L_8 ($4^1 \times 2^3$) ortogonalno matriko. Ovrednotenje eksperimentalnih rezultatov je temeljilo na razmerju *S/N* (angl.: signal/noise ratio *S/N*) oz. primerjavi med nivojem željenega signala in nivojem motnje v ozadju. Avtor študije je izbral kontrolne faktorje, ki so mu omogočali pridobivanje vrednosti za optimalno površinsko hrapavost na osnovi Taguchijeve metode. Izbral je naslednje kontrolne faktorje: štiri različne hitrosti rezanja (100, 150, 200, 250) m/min, dve različni hitrosti podajanja (0,1 in 0,2) mm/obrat, dve globini reza (0,12 in 0,16) mm in dva načina hlajenja (suho in mokro). Učinek nivojev kontrolnih faktorjev na površinsko hrapavost je ovrednotil z analizo variance (ANOVA) eksperimentalnih rezultatov. Izvedel je večstopenjsko regresijsko analizo eksperimentalnih rezultatov. Največji korelacijski koeficient (R^2) je dobil z modelno linearno regresijo in sicer za hrapavost R_a 0,923. V zaključku je izvedel potrditvene teste, ki so mu potrdili, da je optimizacija izvršena zadovoljivo. S Taguchijevo analizo je našel parametre mehanske obdelave za doseganje optimalne površinske hrapavosti. Ti so: hitrost rezanja 150 m/min, hitrost podajanja 0,1 mm/obrat, globina reza 0,16 mm in mokro hlajenje. Rezultati izračunov in potrditvenih testov so dali vrednosti za R_a 0,288 µm in 0,296 µm.

Ključne besede: jeklo AISI P20+S, zaključno rezkanje, Taguchi metoda, površinska hrapavost

1 INTRODUCTION

Products made in plastic-molds are part of our everyday life. Mobile phones, glasses, computer cases, automobile parts, various items of office equipment and many other products are produced in these molds. However, the materials required to make these molds often require unique and compelling properties. For this reason, it is very important to choose the correct steel grade for a special mold. The selection of the right tool steel is a well-known problem. It is not right to choose of the plastic-mold material depending on the properties such as hardness and corrosive properties. When selecting the steel expected to be integrated in a mold material, many parameters such as surface gloss, surface properties, mold-steel workability, weldability and polishability must be considered. The AISI P20+S plastic-mold steel has a wide range of applications due to its easy machinability, good polishability, high tensile strength, high toughness and optimal mechanical properties. These steels, usually used for injection molds, are used in the manufacture of vehicle accessories, office machines and vehicles, general machine parts and various tools. Many machining experiments are needed to optimize the parameters affecting the surface roughness of these commonly used materials. This significantly increases the processing time and cost.

The Taguchi experiment-design method is a successful method of solving optimization problems by increasing the processing performance with fewer experiments and a lower cost.[1] Due to the orthogonal arrays it has developed, this method significantly reduces the number of experiments, thereby preventing the loss of time and cost. Another great advantage of the Taguchi method is that it can predict the end result.[2] The solution obtained with the Taguchi method does not only provide the minimum number of experiments required; it also improves processes and products, supporting high quality in all respects. It shows the minimum sensitivity of a process or product to the production conditions and uncontrollable factors. By providing the necessary tolerances at the lowest cost and a loss function, the Taguchi method leads to a new quality/cost understanding by minimizing the loss caused by the society. Thus, by avoiding unnecessary tests, time and cost savings are provided using the Taguchi method.[3,4]

In the present study, the effects of the factors of cutting speed, feed rate, depth of cut and cooling method on the surface roughness were statistically evaluated for the finish milling of the AISI P20+S die steel, which is widely used in plastic-mold manufacturing. For this purpose, the experiments were designed according to the Taguchi L_8 orthogonal array and the optimal machining-parameter values allowing the lowest surface roughness were determined. For the experimental results, a multiple-regression analysis was performed. At the same time, the effects of the control factors on the surface roughness (R_a) were determined with ANOVA. Finally, the validation of the optimization was tested with confirmation experiments.

2 EXPERIMENTAL PART

2.1 Test specimen and the experimental set-up

This study aimed to determine the optimum machining conditions by investigating the effects of the milling parameters on the surface roughness in the finish milling of the AISI P20+S (235 HB) plastic-mold steel. The plastic-mold steel used in the tests was manufactured with workpiece dimensions of (200 × 100 × 20) mm, and its chemical composition is given in **Table 1**.

Table 1: Chemical composition of AISI P20+S steel

C	Mn	Cr	Mo	S	Fe
0.40	1.50	1.90	0.20	0.050	95.95

The CNC milling machine used in the experiments is an AWEA AF 650 model with a 15-KW drive motor. In the finish-milling experiments, carbide cutting tools coated with PVD-TiAlN, with an IC 900 coated spherical tip (Ø10 mm) obtained from ISCAR were used. The measurement and evaluation of the surface roughness are very important in the machinability studies. For the measurements of the surface roughness of the machined surfaces, a Taylor Hobson Surtronic 25 surface-roughness tester was used. The surface-roughness (R_a) value was calculated as the average of three measurements taken from the machined surfaces.

2.2 Taguchi experimental design

In the experimental studies, it is necessary to design an experiment correctly in order to reach the right result. Consequently, the Taguchi method was used for the experimental design and analysis. In this approach developed by Genichi Taguchi, a statistical performance measure known as the signal/noise (*S/N*) ratio is used to analyze the results. The results obtained with the experiments are evaluated by converting the *S/N* ratio, in which S is the signal factor (the actual value from the system) and N is the noise factor (a factor not included in the experimental design, but influencing the experimental result). Noise sources are all the variables that cause the desired performance characteristics to deviate from the target value. In the calculation of *S/N* ratios, the "nominal is best" (depending on the characteristic type), the "largest is best" and the "smallest is best" methods are used.[1,5] For the determination of the *S/N* values in this study, the formula corresponding to the "smallest is best" principle given in Equation (1) was used since the lowest R_a value was desirable in terms of machining efficiency.

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

Here, y_i is the measured surface roughness value and n is the number of tests performed. The machining parameters chosen were the cutting speed (V), feed rate (f), depth of cut (a) and cooling method (C_m). The control factors and levels used in the finish milling of the AISI P20+S plastic-mold steel are given in **Table 2**. The L_8 mixed orthogonal array shown in **Table 3** was used for conducting the experiments. Applying ANOVA at a 95-% CI on the experimental results, the effects of the variables on R_a were determined. The experimental design and statistical analysis of the Taguchi method were performed using the Minitab 16 software.

Table 2: Control factors and levels

Symbol	Control factors	Level 1	Level 2	Level 3	Level 4
A	Cutting speed – V (m/min)	100	150	200	250
B	Feed rate – f (mm/rev)	0.1	0.2	-	-
C	Depth of cut – a (mm)	0.12	0.16	-	-
D	Cooling method – C_m	1 (dry)	2 (wet)	-	-

Table 3: Taguchi L_8 design with orthogonal array ($4^1 \times 2^3$)

Experiment number	Factor A	Factor B	Factor C	Factor D
1	1	1	1	1
2	1	2	2	2
3	2	1	1	2
4	2	2	2	1
5	3	1	2	1
6	3	2	1	2
7	4	1	2	2
8	4	2	1	1

3 FINDINGS AND DISCUSSION

3.1 Evaluation of the surface-roughness results

The variation in the surface roughness depended on the milling parameters given in **Figure 1**. When the changes in the surface roughness due to the cutting speed were examined, the tendency of the R_a values to decrease with the increasing cutting speed was observed for all the parameters. Increases in the cutting speed reduce the tool-to-chip contact area, thereby reducing the friction, which allows a better surface quality to be achieved. However, at a high cutting speed (200 m/min), some increase in the R_a values was observed. This can be explained with the rising temperature in the cutting zone at high cutting speeds and the increased tool wear due to the increased load on the cutting tool. The R_a measured on all the tools increased in parallel with the increasing feed rate. Increasing the feed rate causes the cutting forces and vibration to increase along with an escalation of the chip volume lifted by the unit, all of which lead to an increased surface roughness.[6] The figure reveals that the surface roughness decreased when the coolant was used. This is attributed to the lubrication and cooling properties of the cutting fluid. Most of the cutting-tool wear results from high temperatures that occur in the cutting zone. Since these temperatures are minimized by the cutting fluid, the surface roughness is improved by reducing the tool wear.[6]

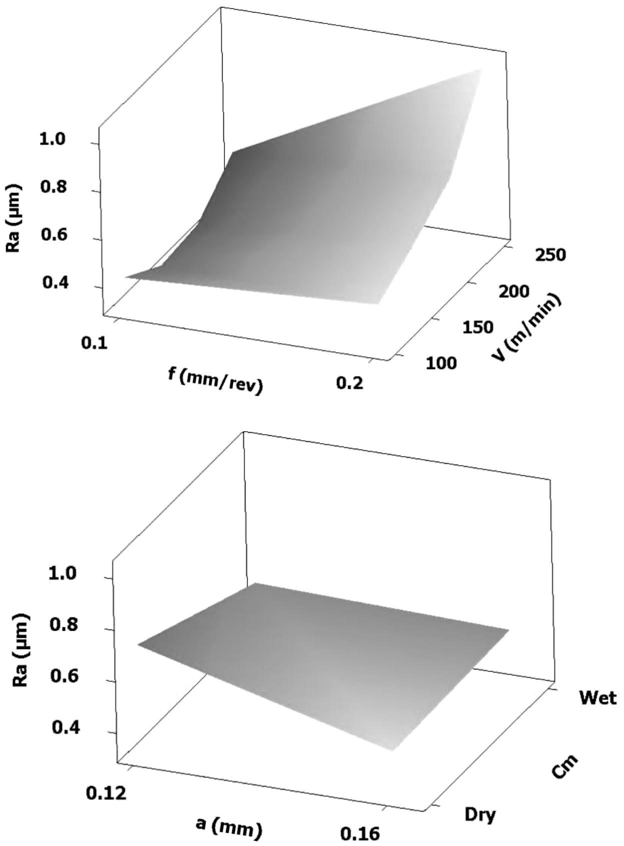

Figure 1: Effects of milling parameters on the surface roughness

3.2 Optimization of the surface roughness

The *S/N* ratios calculated on the basis of the R_a values obtained as a result of the finish-milling tests performed on the AISI P20+S plastic-mold steel according to the Taguchi L_8 test design are given in **Table 4**.

Table 4: Experimental design, R_a and *S/N* ratios

Experiment number	(A) Cutting speed (m/min)	(B) Feed rate (mm/rev)	(C) Depth of cut (mm)	(D) Cooling method	Surface roughness R_a (µm)	R_a – *S/N* ratio (dB)
1	100	0.1	0.12	1	0.42667	7.39823
2	100	0.2	0.16	2	0.48000	6.37518
3	150	0.1	0.12	2	0.32667	9.71790
4	150	0.2	0.16	1	0.58667	4.63217
5	200	0.1	0.16	1	0.34667	9.20176
6	200	0.2	0.12	2	0.70667	3.01571
7	250	0.1	0.16	2	0.50000	6.02060
8	250	0.2	0.12	1	1.02667	-0.22859

Cooling method = 1 (dry) 2 (wet)

The *S/N* responses generated by the Taguchi method were used to determine the most effective control factors at the optimum levels and performance characteristics (surface roughness). The highest S/N values in this table show the optimum level of each control factor. The *S/N* responses showing the effect of each control factor on the surface roughness are given in **Table 5**.

Table 5: *S/N* response table

Levels	Control factors			
	A Cutting speed (m/min)	B Feed rate (mm/rev)	C Depth of cut (mm)	D Cooling method (dry/wet)
Level 1	6.887	8.085	4.976	5.251
Level 2	7.175	3.449	6.557	6.282
Level 3	6.109			
Level 4	2.896			
Delta	4.279	4.636	1.582	1.031
Range	2	1	3	4

When **Table 5** is examined, it can be seen that the most effective factors for the surface roughness were the feed rate, cutting speed, depth of cut and cooling method. These results were confirmed with ANOVA. Moreover, the optimum surface roughness for the finish milling of the AISI P20+S mold steel was obtained at the second level (A2) of the cutting speed, at the first level (B1) of the feed rate, at the second level (C2) of the depth of cut and at the second level (D2) of the cooling method.

The main effect graph showing the optimum values of the control factors, i.e., the machining parameters, is given in **Figure 2**. As in the *S/N* response table, the highest *S/N* values in the main effect graph show the optimum level for that parameter. Thus, the optimum

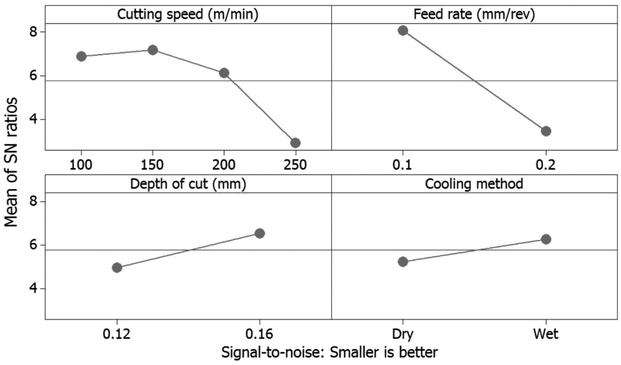

Figure 2: Main-effect plot for *S/N* ratios

values for the surface roughness determined for the cutting speed, feed rate, depth of cut and cooling method were 150 m/min, 0.1 mm/rev, 0.16 mm and wet milling, respectively.

3.3 Analysis of variance

A variance analysis was performed to determine how all the control factors used in the experimental design influenced each other, what effect this had on the performance characteristics, and what kind of changes occurred in the performance characteristics at the different levels of the parameters. The ANOVA results for the effects of the control factors on the surface roughness are given in **Table 6**. Here, the *F* values and the percentage-contribution ratio (PCR) showing the significance level of each variable can be seen. This analysis was performed at the 95-% CI and 5-% significance level. The effect of the control factors was determined by comparing the *F* values. The *F* value is the biggest factor, exerting the largest influence on the result.

Table 6: ANOVA table

Source	Degree of freedom (DF)	Sum of squares (SS)	Mean square (MS)	*F*	P	PCR (%)
Cutting speed (m/min)	3	0.128222	0.042741	213.70	0.050	34.95
Feed rate (mm/rev)	1	0.180000	0.180000	900.00	0.021	49.05
Depth of cut (mm)	1	0.041089	0.041089	205.44	0.044	11.20
Cooling method	1	0.017422	0.017422	87.11	0.068	4.75
Error	1	0.000200	0.000200			0.05
Total	7	0.366933				100

According to the ANOVA results, the most important parameter affecting the surface roughness was found to be the feed rate (49.05 %). This was followed by the cutting speed (34.95 %) and the depth of cut (11.20 %) while the cooling method affected the R_a value at low levels (4.75 %). The results of the *S/N* responses in **Table 5** and the results of the main effect graphs in **Figures 1** were verified by ANOVA.

3.4 Multiple regression analysis of the surface roughness

Regression analysis is a statistical analysis used to transform a criterion variable into an interesting quantification of one or more estimation variables.[7] In this study, the independent variables were the cutting speed (V), feed rate (f), depth of cut (a) and cooling method (C_m), whereas the dependent variable was the surface roughness (R_a). Multiple regression analysis was used to obtain predictive equations for R_a, as seen in Equation (3.1).

$$R_a = 0.392 + 0.00200\ V + 3.00\ f - 3.58\ a - 0.0933\ C_m \tag{3.1}$$

The R^2 value of the equation obtained with the linear regression model for R_a was found to be 0.923. Hence, more intensive predicted values were obtained with the linear-regression model. As a result, the linear-regression model was shown to be successful for the estimation of the surface roughness. The statistical results obtained through the linear regression analysis for the surface roughness are given in **Figures 3** and **4**.

The normal probability plot of the linear model (**Figure 3**) shows that the residuals lie reasonably close to the straight line. This means the errors are distributed nor-

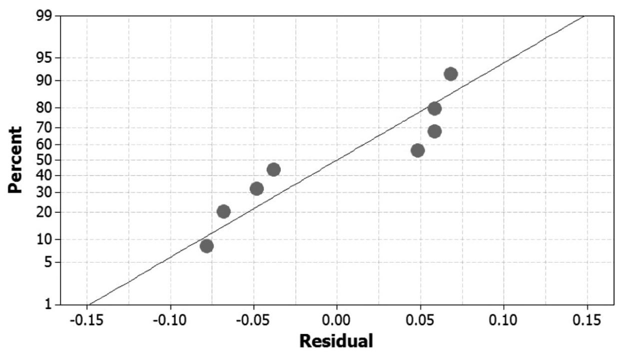

Figure 3: Normal probability plot of the residuals for the surface roughness (R_a)

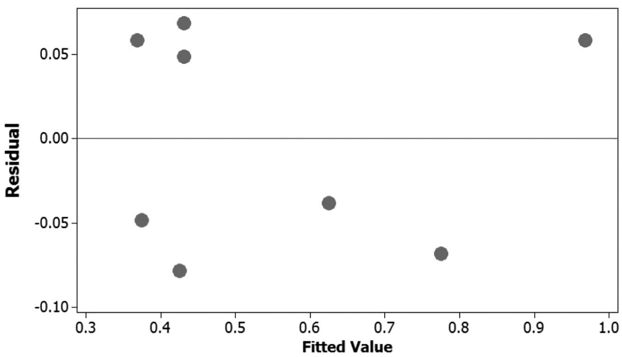

Figure 4: Residuals versus fits plot for the surface roughness

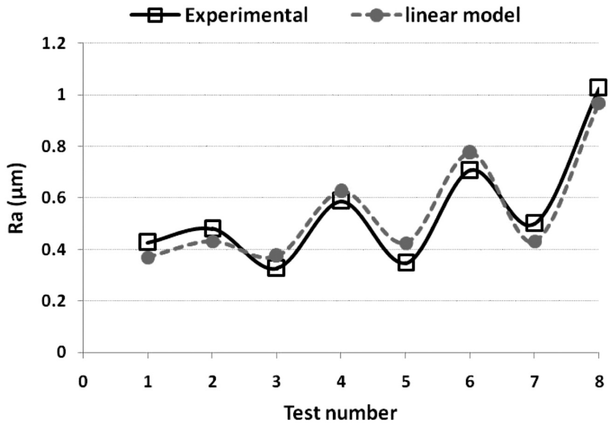

Figure 5: Comparison between measured and predicted values for the surface roughness

mally and the terms mentioned in the model are significant. In addition, the experimental versus predicted values of R_a are found to be very close to each other (**Figure 3**) and the correlation between them is good.[8] The maximum-residual value for R_a of 0.068 was within acceptable limits, thus indicating the significance of the generated model. The residuals versus fits plot for R_a is given in **Figure 4** where the maximum deviation values vary between 0.07 and -0.10 for the surface roughness. As seen from this figure, the model developed using the linear regression analysis can be utilized to accurately predict the surface roughness in finish milling. The differences between the measured and predicted responses are illustrated in **Figure 5**. The values obtained with the linear regression model are closer to the experimental results in terms of R_a. Consequently, these figures indicate that linear models are capable of representing a system under a given experimental domain.

3.5 Confirmation tests

Using the Taguchi optimization method, the optimal results for the surface-roughness values were obtained in the experimental study and ANOVA analyses were performed to determine the percentage distributions of the parameters effective on the result. The final step of the optimization process was to perform confirmation experiments to test the validity of the optimization process. Equations (2) and (3) were used to calculate the surface-roughness values under the optimum milling conditions determined by the Taguchi method.[9] As a result of the calculations using these equations under the optimum conditions, the surface-roughness value was found to be 0.288 µm.

$$\eta_g = \overline{\eta}_g + (\overline{A}_2 - \overline{\eta}_g) + (\overline{B}_1 - \overline{\eta}_g) + (\overline{C}_2 - \overline{\eta}_g) + (\overline{D}_2 - \overline{\eta}_g) \quad (2)$$

$$R_{a_{cal}} = 10^{-\eta_g/20} \quad (3)$$

Here η_G is the *S/N* ratio calculated for the optimum levels, $\overline{\eta}_G$ is the average of the *S/N* ratios of all the variables, $\overline{A}_2$ is the optimum level of the *S/N* ratio of the A factor, $\overline{B}_1$ is the optimum level of the *S/N* ratio of the B factor, $\overline{C}_2$ is the optimum level of the *S/N* ratio of the C factor, $\overline{D}_2$ is the optimum level of the *S/N* ratio of the D factor and R_{acal} is the calculated surface roughness for the optimum level.

For Equation (4), $F_{\alpha,1,fe}$ is the *F* ratio at 95-% CI, a is the level of significance, f_e is the degrees of freedom of error, V_e is the error variance, n_{eff} is the effective number of replications, and *R* is the number of replications for the confirmation experiments. For Equation (5), N is the total number of experiments, and T_{dof} is the total main factor degrees of freedom.

$$CI_{R_a,Vb} = \sqrt{F_{\alpha,1,fe} \cdot V_e \left[\frac{1}{n_{eff}} + \frac{1}{R} \right]} \quad (4)$$

$$n_{eff} = \frac{N}{1 + T_{dof}} \quad (5)$$

$F_{0.05,1,1}$ = 161.45 (from *F* test table), V_e = 0.000200 (**Table 6**), *R* = 3 (Equation (4)).

N = 3, T_{dof} = 6 and n_{eff} = 3 (Equation (5)).

Using Equations (4) and (5), the CI was calculated as $CI_{Ra} = \pm 0.146$. The average optimum R_a (95-% CI) was:

$(R_{a\ opt} - CI_{Ra}) < R_{a\ exp} < (R_{a\ opt} + CI_{Ra}) = (0.288 - 0.146) < 0.296 < (0.288 + 0.146) = 0.142 < 0.296 < 0.434$

The experimental values of $R_{a\ exp}$ fell within the acceptable CI limits. Consequently, the system for R_a was successfully optimized via the Taguchi method (*p* = 0.05). The results obtained from the confirmation experiments reflect the success of the optimization performed. Confirmation tests for the control factors were made via the Taguchi method at optimum and random levels. **Table 7** shows a comparison of the test results with the predicted values obtained using the Taguchi method. The predicted values and the experimental values were very close to each other. For reliable statistical analyses, the error values must be less than 20 %.[10] When the roughness values in **Table 7** are compared, it is noticeable that the difference between the confirmation test results and the results obtained with the Taguchi approach is at an insignificant level. Therefore, the results obtained with the confirmation tests reflect a successful optimization.

Table 7: Predicted and confirmation test results

Levels	R_a (µm)		
	Exp.	Pred.	Error (%)
$A_2B_1C_2D_2$ (Opt.)	0.296	0.288	2.77
$A_3B_1C_1D_1$ (Random)	0.460	0.440	4.54

4 CONCLUSIONS

In this study, a series of finish-milling experiments were carried out for machining the AISI P20+S plastic-mold steel with a hardness of 235 HB, with coated carbide cutting tools at different cutting parameters. Experiments were designed according to the orthogonal array of Taguchi L_8 and they provided the optimum surface-roughness values with 8 experiments instead of 32 experiments in a shorter time, resulting in time and cost savings. The effects of the milling parameters on the surface roughness were determined with an analysis of variance. The experimental results were estimated with a multiple regression analysis. The validity of the optimization was tested with the confirmation experiments. The results obtained in this context are as follows:

The optimum values were obtained by taking the highest values of the average *S/N* ratios, thus determining the best result for the surface roughness to be found at the second level of the cutting speed (150 m/min), the first level of the feed rate (0.1 mm/rev), the second level of the depth of cut (0.16 mm) and the second level of the cooling method (wet).

According to the ANOVA results, the most effective parameter on the R_a was the feed rate (49.05 %), followed by the cutting speed (34.95 %), the depth of cut (11.20 %) and the cooling method (4.75%).

The results of the confirmation test showed the measured values to fall within the confidence interval (CI) of 95 %.

The developed linear regression models demonstrated a very good relationship with high correlation coefficients (R_a = 0.923) between the measured and predicted values for the surface roughness.

After the calculation and the confirmation experiments, the surface-roughness values under the optimum milling conditions were found to be 0.288 μm and 0.296 μm, respectively.

The optimization results demonstrated that the Taguchi experimental-design method had been successfully applied to determine the optimum surface roughness of the AISI P20+S plastic-mold steel in finish milling.

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