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Modeling and optimization of finish diamond turning of spherical surfaces based on response surface methodology and cuckoo search algorithm

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A B S T R A C T

Surface roughness is one of the most significant factors to indicate the product quality. Diamond turning is an efficient and highly accurate material removal process to improve the surface quality of the workpiece. In the present study, the arithmetic mean absolute roughness (R_a) and total height of profile (R_t) of spherical surface during finish turning of a commercial brass alloy CuZn40Pb2 were modeled using Response Surface Methodology (RSM). The experimental investigations were carried out using the Central Composite Design (CCD) under dry conditions. The effect of cutting parameters such as spindle speed, feed rate and depth of cut) on spherical surface quality was analyzed using analysis of variance (ANOVA). A cuckoo search (CS) algorithm was used to determine the optimum machining parameters to minimize the surface roughness. Finally, confirmation experiments were carried out to verify the adequacy of the considered optimization algorithm.

A R T I C L E I N F O

Keywords:
Brass alloy;
Diamond turning;
Surface roughness;
Spherical surface;
Modeling;
Optimization;
Response surface methodology (RSM);
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1. Introduction

Brass (copper-zinc) alloys are used in a wide range of industrial applications such as mechanical, electrical and hydraulic systems due to their excellent formability, high thermal and electrical conductivity, corrosion resistance and excellent antibacterial properties. To improve machinability, various alloying elements are commonly added to brass. The most important of these elements is lead, which improves machinability in terms of tool wear, cutting forces, chip breaking and surface quality [1-3]. Extensive research has been carried out in recent decades to improve the machinability of brass alloys.

In [4], a comparison of the machinability of three lead-free brass alloys and one leaded brass alloy in terms of energy consumption and chip morphology was carried out. The influence of different coating types and the use of diamond tools on cutting forces, chip formation and surface quality was investigated by Klocke *et al.* [5]. Nobel *et al.* [6] analyzed the chip formation process in different low lead brass alloys. Schultheiss *et al.* [7] analyzed cutting forces, surface quality and tool wear during longitudinal turning to evaluate the machinability of leaded and lead-free brass alloys. The effects of minimum quantity lubrication (MQL) and cutting parameters on surface quality during turning of commercial brass were studied by Davim *et al.* [8]. A comparison with conventional flooding conditions was also made. The machinability of the highly leaded brass alloy CuZn39Pb3 [9] and commercial lead-free brass alloys [10] was also analyzed. Vilarinho *et al.* [11] studied the influence of the chemical composition of brass alloys on surface quality and machining forces during turning. Schultheiss *et al.* [12] compared the machinability and manufacturing costs in turning of conventional leaded brass alloys and a low-lead alternative. Toulfatzis *et al.* [13] studied the chip morphology and tool wear during longitudinal turning of two leaded brass alloys. The Taguchi method with the utility concept was introduced for simultaneous optimization of surface quality and specific cutting force in turning of brass CuZn39Pb3 under MQL cutting [14]. Toulfatzis *et al.* [15] used the signal-to-noise ratio for single optimization of surface roughness and cutting force in longitudinal turning of lead-free and leaded brass alloys.

Some researchers also used artificial intelligence based methods. Gaitonde *et al.* [16] applied a genetic algorithm to determine the optimum machining parameters for minimizing surface roughness when turning leaded brass alloys under MQL conditions. Raja and Baskar [17] presented a multi-objective optimization method based on particle swarm optimization with two objectives, namely machining time and surface quality. Optimum cutting conditions during turning for different materials namely brass, aluminum, mild steel and copper were selected. Natarajan *et al.* [18] estimated the surface roughness in longitudinal turning of brass using artificial neural networks.

After a review of the literature, it is apparent that a considerable amount of research has been conducted on turning of brass alloys. However, none of the literature reviewed dealt with finish diamond turning of spherical surfaces. As market competitiveness increases, surface roughness is probably one of the most widely used indicators of surface quality of machined parts today [19-27]. Surface roughness affects several functional properties of products, especially friction, fatigue strength, wear, heat transfer, light reflection, lubricant distribution, etc. Ensuring surface quality is one of the most critical issues in the fully automated mass production of parts with spherical surfaces. However, surface roughness is strongly influenced by the variation of process parameters and analytical modeling is difficult due to its nonlinearity. Therefore, it is imperative to develop a mathematical model of surface roughness, exploit the influence of machining parameters, and finally optimize the surface quality in brass ball turning.

2. Experimental procedure

The machining tests were performed on the special machine tool Picchi Diamantatrice to produce spherical parts with a spindle power of 5.5 kW and a maximum spindle speed of 7000 rpm. This lathe was equipped with two tools: a carbide turning tool for roughing and a diamond tool for finishing and machines spheres with a diameter of 2" (Fig. 1). Commercially available brass CuZn40Pb2 (CW617N) workpieces were used for machining. The chemical composition of the material is summarized in Table 1. The working material has a hardness of 90-100 HRB and a tensile strength of 390-440 N/mm^2. This alloy provides good corrosion resistance together with good formability.

Table 1 Chemical composition of the studied brass alloys

Alloy	Cu (%)	Zn (%)	Pb (%)	Al (%)	Fe (%)	Ni (%)	Sn (%)	Others: Mn, Si, Sb, As, Bi, (%)
CuZn40Pb2	57-59	rest	1.6-2.5	0.05 max	0.3 max	0.3 max	0.3 max	0.2 max

The diamond cutting tool was used for precision machining of a ball valve. The tool nose does not have a radius like conventional cutting tools, but a flat nose that allows very fine machining. The dimensions of the tool were 95 × 12 × 12 mm, with the sides at a 45° angle and a 1.3 mm wide cutting edge. The main angles of the tool cutting wedge were 2° for clearance angle α, -10.5° for rake angle γ and consequently 98.5° for wedge angle β. The cutting depth of the diamond segment is 0.4 mm and represents the maximum theoretical cutting depth, but due to the possibility of pulling the diamond segment out of the tool holder, the depth of cut is usually not used deeper than 0.2 mm.

Fig. 1 Experimental setup for diamond fine turning of CuZn40Pb2

The arithmetic mean of the absolute roughness (R_a) and a total height of profile (R_t) of the machined workpiece were measured with the surface roughness measuring device Tesa Rugosurf 20 (Fig. 2). The examined length was 3.2 mm with a basic span of 0.8 mm.

Fig. 2 Surface roughness measurements

In the present study, three cutting parameters, i.e., spindle speed (n), feed rate (f) and depth of cut (a) were selected, and the ranges of machining conditions were defined through initial experiments. The cutting parameters and their levels are given in Table 2.

The experiments were designed and carried out according to the Central Composite Design (CCD). All experiments were conducted under dry conditions. The measured values of R_a and R_t are shown in Table 3.

Table 2 Machining parameters and their levels

Parameter	Unit	Levels		
		Level 1	Level 2	Level 3
Spindle speed, n	min^{-1}	4800	5500	6200
Feed, f	mm/rev	0.48	0.64	0.80
Depth of cut, a	mm	0.075	0.125	0.175

Table 3 Experimental layout for central composite design

No.	Process parameters			Response measurements	
	n (min^{-1})	f (mm/rev)	a (mm)	R_a (μm)	R_t (μm)
1	5500	0.64	0.125	0.140	0.97
2	4800	0.48	0.075	0.208	1.38
3	6200	0.80	0.075	0.164	1.11
4	5500	0.48	0.125	0.173	1.18
5	4800	0.48	0.175	0.212	1.76
6	4800	0.80	0.075	0.249	2.10
7	5500	0.64	0.125	0.154	1.00
8	6200	0.64	0.125	0.155	1.07
9	5500	0.80	0.125	0.152	1.11
10	4800	0.64	0.125	0.179	1.29
11	5500	0.64	0.125	0.156	1.06
12	5500	0.64	0.075	0.149	1.05
13	4800	0.80	0.175	0.224	1.56
14	6200	0.80	0.175	0.150	1.14
15	6200	0.48	0.175	0.215	1.56
16	6200	0.48	0.075	0.145	1.35
17	5500	0.64	0.175	0.218	1.51

3. Results and discussion

The reduced quadratic polynomial model, given as a function of the machining parameters for an arithmetic mean of the absolute roughness (R_a) and a total height of the profile (R_t) using the Response Surface Methodology (RSM) is represented by Eq. 1 and Eq. 2, respectively

$$R_a = 0.4063 - 3.4714 \cdot 10^{-5} n + 0.212 f - 2.1591 a - 1.7656 fa + 13.9886 a^2 \tag{1}$$

$$R_t = 8.5175 - 3.2011 \cdot 10^{-3} n + 9.2605 f - 14.7502 a - 1.317 \cdot 10^{-3} nf - 17.1875 fa + 3.4347 \cdot 10^{-7} n^2 + 107.3208 a^2 \tag{2}$$

The adequacy of the developed models was examined using analysis of variance (ANOVA). The results are given in Table 4 and Table 5 for R_a and R_t, respectively. The F-values for R_a and R_t are 5.80 and 7.85, respectively. For the desired confidence level (95 %), the F-values of the established model exceed the F-value of the standard tabulated F-values for R_a and R_t of 3.204 and 3.293, respectively. Thus, the two reduced quadratic models can be considered appropriate within the confidence limit. P-values smaller than 0.05 imply that n and the product a^2 are statistically significant terms for the arithmetic mean of absolute roughness R_a, while n and the products $n \times f$, $f \times a$ and a^2 are also observed to be significant terms for the total height of the profile R_t. Other parameters have no statistical significance for the surface quality responses considered. The squared correlation coefficient (R^2) values of 0.7250 and 0.8593 for R_a and R_t, respectively, show good agreement among the experimental and predicted values for both models.

The 3D response surfaces were also created to study the effects of the machining parameters and their interactions. Figs. 3-5 show the contour plots for the surface roughness parameters (R_a and R_t) as a function of spindle speed (n), feed rate (f) and depth of cut (a).

Table 4 The ANOVA table for R_a

Source	Sum of squares	DF	Mean square	F-value	P-value
Model	0.014	5	$2.728 \cdot 10^{-3}$	5.80	0.0073
n	$5.905 \cdot 10^{-3}$	1	$5.905 \cdot 10^{-3}$	12.56	0.0046
f	$1.96 \cdot 10^{-5}$	1	$1.96 \cdot 10^{-5}$	0.042	0.8419
a	$1.082 \cdot 10^{-3}$	1	$1.082 \cdot 10^{-3}$	2.30	0.1575
$f \times a$	$1.596 \cdot 10^{-3}$	1	$1.596 \cdot 10^{-3}$	3.39	0.0925
a^2	$5.036 \cdot 10^{-3}$	1	$5.036 \cdot 10^{-3}$	10.71	0.0074
Error	$5.172 \cdot 10^{-3}$	11	$4.072 \cdot 10^{-4}$		
Total	0.019	16			

Table 5 The ANOVA table for R_t

Source	Sum of squares	DF	Mean square	F-value	P-value
Model	1.31	7	0.19	7.85	0.0031
n	0.35	1	0.35	14.53	0.0041
f	$4.41 \cdot 10^{-3}$	1	$4.41 \cdot 10^{-3}$	0.19	0.677
a	0.029	1	0.029	1.22	0.2971
$n \times f$	0.17	1	0.17	7.31	0.0242
$f \times a$	0.15	1	0.15	6.35	0.0327
n^2	0.086	1	0.086	3.60	0.0902
a^2	0.22	1	0.22	9.16	0.0143
Error	0.21	9	0.024		
Total	1.52	16			

The effects of spindle speed and feed rate on roughness parameters are shown in Fig. 3, where the depth of cut is kept at an intermediate level. The minimum value of R_a was obtained at high spindle speed and low feed rate, as shown in Fig. 3a. It should also be noted that the R_a value is almost directly proportional to these two parameters, with feed rate having less significance. Fig. 3b shows that R_t is significantly affected by spindle speed, while feed rate has less influence on it. The minimum value of R_t was also found at the maximum values of spindle speed and feed rate. Therefore, to obtain better roughness parameters, higher spindle speeds and feed rate should be preferred for diamond finish turning of spherical surfaces.

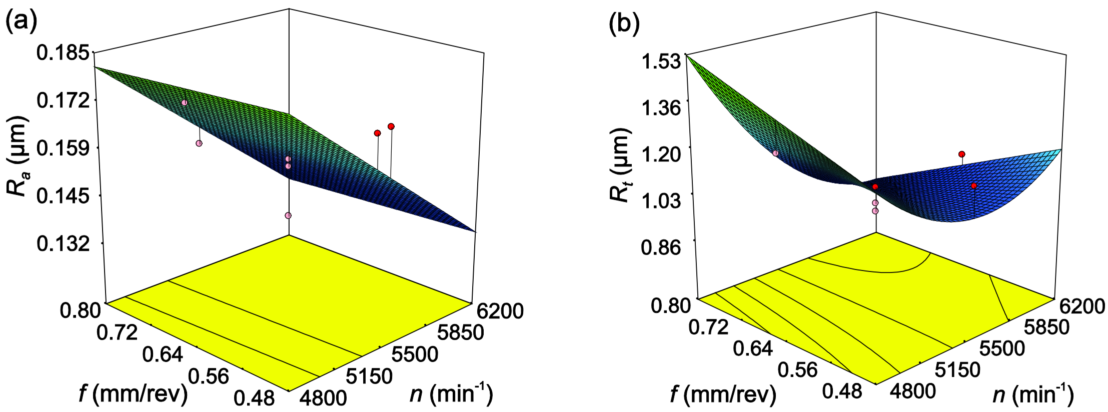

Fig. 3 Surface plot of R_a (a) and R_t (b) with spindle speed and feed rate

Fig. 4 shows the estimated response surface with respect to the spindle speed and the depth of cut, while the feed rate is kept at an intermediate level. The minimum values of both parameters were obtained at high spindle speed and medium depth of cut. It can also be observed that both cutting parameters strongly influence the surface quality.

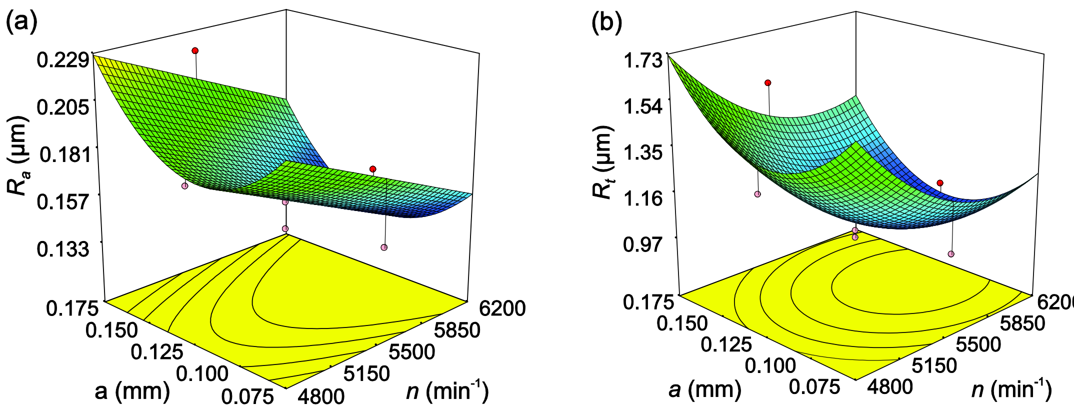

Fig. 4 Surface plot of R_a (a) and R_t (b) with spindle speed and depth of cut

Fig. 5 shows the influences of feed rate and depth of cut on the surface roughness parameters (R_a and R_t), while the spindle speed is kept at an intermediate level. The plots show that the minimum values for both parameters were found at a high feed rate, while the depth of cut was about 0.1 mm. This figure shows that both roughness parameters are almost directly proportional to the feed rate. It is also worth noting that the depth of cut is more significant compared to the feed rate.

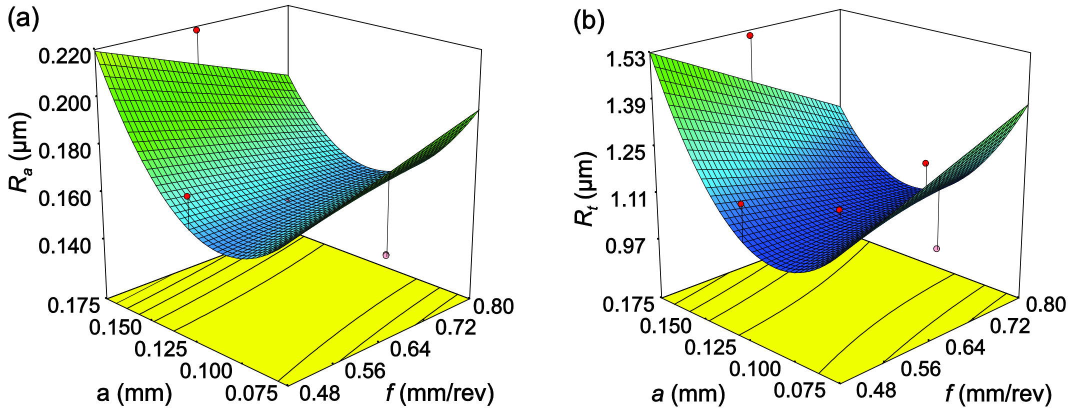

Fig. 5 Surface plot of R_a (a) and R_t (b) with feed rate and depth of cut

4. Optimization

4.1 Cuckoo search

The cuckoo search (CS) algorithm, originally introduced by Yang and Deb [28], is one of the recent swarm intelligence-based optimization algorithms. The CS algorithm was inspired by the brood parasitism behavior of certain cuckoo bird species and the characteristics of Lévy flights discovered in the flight behavior of numerous insects and animals. Female cuckoos lay their eggs in the nests of other, typically different species of host birds. These eggs also resemble the host birds' eggs in color and pattern. When the host bird realizes that the eggs are not its own, it either discards them or simply leaves the nest and builds a new one elsewhere. Cuckoos must therefore mimic their host birds' eggs very closely to minimize the likelihood that their eggs will be abandoned. Optimization is about replacing a less good nesting solution with a new and potentially better one (cuckoo).

The CS algorithm is essentially based on three idealized rules [29]: (i) each cuckoo lays one egg at a time in a randomly selected nest; (ii) an elite selection procedure is used in which only the best nests with superior quality eggs are passed on to the next generation; (iii) the number of available host nests is fixed and a host bird can detect a foreign egg with probability in the range of [0, 1].

While producing new solutions $x^{(t+1)}$ for the i-th cuckoo, Lévy flight is performed

$$x_i^{(t+1)} = x_i^{(t)} + \alpha \otimes \text{Lévy}(\lambda) \tag{3}$$

where $x^{(t)}_i$ denotes the i-th candidate solution at iteration t and $\alpha > 0$ denotes the step size factor. In most cases, $\alpha = 1$ can be used. The product $\otimes$ denotes inputwise walking for multiplications.

Basically, the Lévy flight results in a random walk, where the random step length is determined by a Lévy distribution with infinite mean and infinite variance

$$\text{Lévy} \sim u = t^{-\lambda}, (1 < \lambda \leq 3) \tag{4}$$

4.2 Optimization model

The optimization process in this paper aims to find the best combination of process parameter levels that results in the lowest value of R_a and R_t. To formulate the optimization problem, the regression models for R_a (Eq. 1) and R_t (Eq. 2) were used as the objective function. In this study, three variables, namely spindle speed, feed rate and depth of cut were considered as optimization variables. Normalization of each subobjective was also introduced to compensate the differences in numerical values between them. Thus, the resulting objective function (ROF) to be minimized is a weighted combination of the two objectives as follows:

$$\mathrm{ROF}\ (n, f, a) = w_1 \frac{R_a}{R_{a\min}} + w_2 \frac{R_t}{R_{t\min}} \tag{5}$$

where w_1 and w_2 are the weight factors of R_a and R_t, respectively. In this paper, equal weights for R_a and R_t were selected, i.e. $w_1 = w_2 = 1/2$.

The minimization of the ROF (Eq. 5) is subject to the limits of the cutting parameters. The boundary conditions were the upper and lower limit of the experimental machining parameters (Table 2) and were given as follows: $4800 \leq n \leq 6200$ min^{-1}, $0.48 \leq f \leq 0.8$ mm/rev, $0.075 \leq a \leq 0.175$ mm.

After formulating the optimization problem and its constraints, the CS optimization algorithm was employed to solve the problem. The proposed CS algorithm requires some setting parameters for implementation. The minimum value of the resulting objective function (ROF = 0.916) was obtained for a population size of 20, termination probability of 0.25, and termination criterion of 100 generations. The results of the CS optimization algorithm showed that the best combination of turning parameters for simultaneous optimization of the arithmetic mean of absolute roughness (R_a) and total height of profile (R_t) was: 6200 min^{-1} for spindle speed, 0.8 mm/rev for feed rate, and 0.13 for depth of cut.

4.3 Confirmation experiments

The confirmation tests were carried out at the optimum values of the process parameters to verify the quality characteristics of the spherical fine turning process recommended in the study. In accordance with the obtained optimum results, four new experiments were carried out (Table 6). The mean values of R_a and R_t were 0.139 µm and 1.04 µm, respectively, which were in good agreement with the predicted values. Consequently, the proposed CS optimization algorithm was efficient to find out the optimal set of machining parameters for spherical finish turning associated with minimum surface roughness.

Table 6 Results of confirmation tests

Confirmation test	1	2	3	4	Mean
R_a (µm)	0.143	0.149	0.134	0.141	0.139
R_t (µm)	1.19	0.89	1.10	0.97	1.04

5. Conclusions

In the present research work, the influence of machining parameters such as spindle speed, feed rate and depth of cut on the arithmetic mean of absolute roughness (R_a) and total height of profile (R_t) in diamond finish turning of brass CuZn40Pb2 was investigated. The following conclusions can be drawn from the analysis of the results, subsequent model development and optimization:

- The response surface methodology in combination with the central composite design has been successfully applied to study the effects of different machining parameters on two quality characteristics, namely the arithmetic mean of the absolute surface roughness and the total profile height, during diamond finish turning of spherical surfaces. The developed mathematical models of both responses in terms of the actual design factors, their interactions and quadratic terms are suitable for the analysis of the sphere turning process.
- The spindle speed and the quadratic term of the depth of cut were the significant parameters affecting the arithmetic mean of the absolute roughness, according to the results of ANOVA. The ANOVA also showed that the spindle speed, the quadratic term of the depth of cut, the interaction terms between the spindle speed and the feed rate, and the feed

rate and the depth of cut were significant terms affecting the performance of the total height of the profile. Spindle speed showed the greatest influence on both surface parameters compared to depth of cut and feed rate.

- The best combination of cutting parameters to simultaneously minimize the arithmetic mean of the absolute roughness and the total height of the profile, obtained by the optimization model based on the cuckoo search algorithm, was as follows: 6200 min-1 for spindle speed, 0.8 mm/rev for feed rate and 0.13 mm for depth of cut. This study and the determined combination of parameters allow a more detailed technology planning for the production of high-quality spherical components, both from the point of view of premachining and productivity itself. The results obtained do not confirm the theory of turning. In fact, in our case, we obtain the best results at the highest feed rate, which is contrary to expectations. This is certainly related to the kinematics and stability of the machine tool in this speed and feed range, which in turn shows how important it is to optimize each machining process.
- The results of the confirmation experiments reveal the effectiveness of the proposed algorithm for optimizing the surface quality characteristics in diamond finish turning of spherical surfaces.

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