Machining Parameter Optimization of EVA Foam Orthotic Shoe Insoles

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Received 16 December 2019; received in revised form 03 March 2020; accepted 19 May 2020

DOI: https://doi.org/10.46604/ijeti.2020.5099

Abstract

In this study, ethylene-vinyl acetate (EVA) foam orthotic shoe insoles with different surface roughnesses (Ra) are investigated in terms of CNC milling strategy. Based on a hybrid Taguchi-response surface methodology (TM-RSM) approach, machining parameters, including tool path strategy, spindle speed, feed rate, and step over, as well as material hardness, are of particular interest. The main aim of this work is to develop mathematical models and determine the optimum machining parameters. Experiments are conducted on a CNC milling machine with a standard milling cutter and run under dry coolants. The optimal conditions are established based on TM and then used to determine the optimum values in the RSM modeling. The main finding of the present work is that there are significant improvements in the Ra, by up 0.24% and 4.13%, and machining time, by up 0.43% and 0.41%, obtained with TM-RSM in comparison to TM analysis.

Keywords: shoe insole, EVA foam, CNC milling, surface roughness (Ra), machining time

1. Introduction

There are three types of shoe soles: the bottom of the shoe that contacts directly with the ground (outsole), the bottom of the shoes attached to the outsole, and the insole is the inside of the shoe that contacts directly with the patient’s feet. Among them, the second provides comfort to the foot during exertion (middle sole), and the insole of the third is located on the inside of the shoe between the outsole and upper shoe. The shoe insole is in direct contact with the human foot while doing daily activities such as walking, running, and jumping. This part is very important in determining whether the user or patient feels comfortable when wearing shoes.

Types of rubber include isobutylene-isoprene rubber, chloroprene rubber, nitrile rubber, silicone rubber, polyurethane, natural rubber, ethylene-propylene rubber, and polybutadiene [1]. While the rubber materials were used as orthotic shoe insoles in the manufacturing industry for EVA, some researchers [2-7] reported that EVA foam shaped like a rubber material, known as EVA foam rubber, is also a popular raw material for insole shoe orthotics (ISO) in the shoe industry. This material proved widely used in the engineering design process for shoe insole manufacturing because of useful properties including good elastomer properties, lightweight, formability, and quite easily processed manufacturing on CNC milling machines. EVA foam rubber is a copolymer formed from the monomers ethylene and vinyl acetate (VA) with resin and rubber [8]. EVA rubber foam also has many applications in sports and medical engineering because it is very good as an energy absorber and has a high fracture toughness relative to other polymers [9]. Besides, this material is consistently used in advanced composites for

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specialized application insole shoe orthotics for a patient with diabetes (ISO diabetes). As a result, these materials are gaining widespread acceptance in the footwear sector at this time because the industry can provide a lighter weight shoe with high comfort, robustness, and durability [9].

ISO diabetes used in footwear to reduce pain and mechanical load on the patient's leg would be better if manufactured using CNC machines. This machine produces ISO diabetes with high surface quality, accuracy, and precision. To generate an ISO product with these requirements, parameters need to be optimized on the optimal cutting CNC machine and its supporting equipment. The imprecise results of conventional foam box methods, which were carried out by several orthotics laboratories in Indonesia, can be minimized using reverse engineering, CAD, CAM, and CNC [6-7]. Surface quality and Ta initially ranging from Ra = 20–30 μm and 1-week working time can be reduced to Ra = 5-9 μm and five to seven hours/pair of orthotic shoes (ISO diabetes). To achieve this highly desirable result, the use of optimization techniques to determine precise machining parameter settings and obtain an optimal response is the research done in this paper. Two statistical methods were used to resolve this problem, Taguchi methodology (TM) and response surface methodology (RSM). These methods were used to help researchers and an ISO engineer solve the problems of determining the insole designs when EVA foam rubber is used.

The objective of this paper is to develop a mathematical model and optimize the manufacturing process parameters using the hybrid TM-RSM approach. This hybrid approach was chosen to develop a mathematical model and optimize the orthotic shoe insole cutting parameters in a CNC milling process on the EVA rubber foam material.

2. Methods

2.1. The 3D design of the shoe insole orthotics

Three types of orthotic shoe insole designs that fit the contour of diabetes mellitus patient's legs were manufactured on a CNC milling machine. According to the results of the work carried out previously [10], reverse innovative design (RID) methods were used to develop a 3D model shoe orthotic insole with the aid of 3D scanning (Handyscan 700TM) in which the surface modeling base curve of the three insole designs can be explored using the CAD software PowerSHAPE 2017. The results of insole design for precise geometric tolerances enlarged along the XY axis ranged from 0.75 to 1.50 mm. Three types of orthotics shoe insole designs that fit with the foot of patients who have were successfully obtained by previous researchers [5-6] and are shown in Fig. 1.

Fig. 1 Top view of 3D CAD model shoe insoles with several size tolerances

2.2. Condition cutting parameters and design of experiments

Six machining parameters were selected and evaluated, namely toolpath strategy (A), spindle speed (B), feed rate (C), step over (D), EVA foam with variable hardness (E), and the type of insole design with wide tolerance (F). Based on all machining parameters in Table 1, the optimal experiment design in this research used the Taguchi methods with Minitab v2017 was an orthogonal array OA L_{27}^{3^6} and is shown in Table 2.
Table 1 Parameter and their machining level for OA $L_{25}^{3^6}$

| Factor | Level                  |
|--------|------------------------|
| A      | Raster 90°             |
| B      | 14000 rpm              |
| C      | 800 mm/min             |
| D      | 0.20 mm                |
| E      | 20–35 HRc ($31$/sheet) |
| F      | 0.50 mm                |

Table 2 Response data surface roughness (Ra) and Ta for OA $L_{25}^{3^6}$

| N exp | Uncoded value of factor | Insole patient 1 | Insole patient 2 | Patient 1 | Patient 2 |
|-------|-------------------------|-------------------|-------------------|-----------|-----------|
|       |                         | µm                | µm                | Minutes   | Minutes   |
| 1     | 1 1 1 1 1 1 1          | 7.671             | 8.594             | 323.32    | 336.39    |
| 2     | 1 1 1 1 2 2            | 8.995             | 9.436             | 319.40    | 334.45    |
| 3     | 1 1 1 1 3 3            | 9.252             | 8.081             | 321.80    | 333.83    |
| 4     | 1 2 2 2 1 1            | 6.969             | 7.716             | 256.44    | 269.35    |
| 5     | 1 2 2 2 2 2            | 8.011             | 8.800             | 254.24    | 268.34    |
| 6     | 1 2 2 2 3 3            | 8.368             | 6.618             | 254.20    | 268.52    |
| 7     | 1 3 3 3 3 1 1          | 7.812             | 8.027             | 214.96    | 229.95    |
| 8     | 1 3 3 3 2 2            | 8.324             | 9.286             | 212.77    | 229.77    |
| 9     | 1 3 3 3 3 3            | 8.527             | 8.319             | 213.89    | 229.80    |
| 10    | 2 1 2 3 1 2            | 7.162             | 7.881             | 229.52    | 245.17    |
| 11    | 2 1 2 3 2 3            | 8.198             | 9.225             | 228.58    | 244.57    |
| 12    | 2 1 2 3 3 1            | 8.080             | 7.496             | 227.78    | 243.88    |
| 13    | 2 2 3 1 1 2            | 7.967             | 8.395             | 301.10    | 315.20    |
| 14    | 2 2 3 1 2 3            | 9.330             | 8.771             | 298.35    | 313.75    |
| 15    | 2 2 3 1 3 1            | 7.659             | 8.897             | 297.52    | 312.44    |
| 16    | 2 3 1 2 1 2            | 8.432             | 7.557             | 276.97    | 290.96    |
| 17    | 2 3 1 2 2 3            | 7.934             | 7.361             | 274.80    | 289.85    |
| 18    | 2 3 1 2 3 1            | 8.417             | 6.890             | 272.55    | 288.78    |
| 19    | 3 1 3 2 1 3            | 7.963             | 8.151             | 273.59    | 289.62    |
| 20    | 3 1 3 2 2 1            | 8.588             | 9.061             | 321.67    | 337.44    |
| 21    | 3 1 3 2 3 2            | 8.822             | 7.970             | 270.45    | 283.65    |
| 22    | 3 2 1 3 1 3            | 8.165             | 7.983             | 271.33    | 286.35    |
| 23    | 3 2 1 3 2 1            | 7.974             | 7.881             | 326.90    | 343.99    |
| 24    | 3 2 1 3 3 2            | 7.554             | 8.047             | 267.33    | 282.33    |
| 25    | 3 3 2 1 1 3            | 8.009             | 6.850             | 327.28    | 341.77    |
| 26    | 3 3 2 1 2 1            | 7.599             | 8.489             | 382.09    | 398.11    |
| 27    | 3 3 2 1 3 2            | 8.372             | 9.008             | 322.65    | 338.53    |

Table 3 Response surface roughness (Ra) for S/N ratios (dB) and the Means effects (m)

| Control factor | Surface roughness Ra (Insole patient 1) | Surface roughness Ra (Insole patient 2) |
|----------------|------------------------------------------|------------------------------------------|
|                | mean level 1 level 2 level 3 SN Ra Delta mean level 1 level 2 level 3 SN Ra Delta |
|                | Mean (µm)  | Mean (µm)  | (dB)      | Mean (µm)  | Mean (µm)  | (dB)      |                      |
| A              | 8.214 8.0958.131 | 26618.0 | 0.119 | 8.320 8.0538.181 | 5637.1 | 0.267 |
| B              | 8.304 8.1588.011 | 4664.21 | 0.293 | 8.433 7.9768.123 | 1848.7 | 0.456 |
| C              | 7.863 8.2778.332 | 1517.19 | 0.469 | 8.009 7.9818.542 | 1040.4 | 0.561 |
| D              | 8.371 7.9898.167 | 3692.73 | 0.328 | 8.502 7.7918.238 | 776.7 | 0.711 |
| E              | 7.794 8.3288.350 | 1007.68 | 0.556 | 7.906 8.7017.925 | 487.28 | 0.795 |
| F              | 8.193 7.8638.443 | 1182.39 | 0.580 | 8.117 7.9328.486 | 1260.0 | 0.554 |
The average Ra for orthotic shoe insoles was measured with a Ra tester (Mark Surf PS 1) in Table 2, and the Ra value obtained is Ra value on average for the second leg of the patient. The response of processing time (Ta) and surface roughness (Ra) for S/N ratios and means effects are shown in Tables (3)-(4).

Table 4 Response processing time (Ta) for S/N ratios (dB) and the effects of Means (hours)

| Control factor | Insole processing time (T_{A1}) | Insole processing time (T_{A2}) |
|----------------|---------------------------------|---------------------------------|
|                | Mean (hour)                     | Mean (hour)                     |
|                | level 1  level 2  level 3       | level 1  level 2  level 3       |
|                | SN Ra  Delta                    | SN Ra  Delta                    |
| A              | 4.391  4.458  5.118             | 4.630  4.707  5.374             |
| B              | 4.659  4.680  4.627             | 4.906  4.926  4.879             |
| C              | 4.916  4.598  4.452             | 5.156  4.848  4.707             |
| D              | 5.359  4.546  4.061             | 5.601  4.784  4.326             |
| E              | 4.583  4.849  4.534             | 4.824  5.106  4.781             |
| F              | 4.858  4.545  4.563             | 5.112  4.793  4.806             |

2.3. Material specimens, machine tools, and cutting tools specification

The EVA foam rubber size used in the experiments for insole manufacture in the CNC milling process was 250 mm x 95 mm x 23 mm. This material has a hardness in the range of 20–60 HRc, was measured by using a shore hardness tester (Asker CL-150). Three types of EVA foam rubber identified based on three hardness levels (Level 1 20–35 HRc, Level 2 35–45 HRc, and Level 3 50–60 HRc). The material prices for 1200 x 2400 x 30 mm sheets in the local market in Jakarta, Indonesia are presented in Table 1. Besides, EVA foam rubber also has a density of 55–65 kg/m³, the nominal size on the market of around 2000 x 1000 mm, thickness (separate) of 3–36 mm, the tensile strength of 800 kPa, and tear strength of 4.5 kN/m [2]. The test
CNC milling process on the EVA foam rubber made the used maximum spindle speeds up to 17,000 rpm and 100 W DC-power spindle motors. The used cutting tools were made from carbide milling cutter endmill type SECO [93060F] and ball-nose milling cutter [JS533060D1B0Z3 -NXT]. Material specimens, outputs, and a flowchart of the research are presented in Figs. (2)-(3).

3. Results and Discussion

In this study, the value of Ra was obtained from experiments varying the cutting parameters for the orthotic shoe insole manufacturing process in a Roland MDX 40R CNC machine, and the results are shown in Table 2. The effect or influence arising from any level of the factors on quality characteristics was analyzed using the signal-to-noise ratio. Different values of SNR between the maximum and minimum (main effect) are presented in Tables (3)-(4). For Ra of the shoe insole orthotics for Patient 2, the optimum value can be achieved if conditions are set at Level 2 for factors toolpath strategy (A), spindle speed (B), feed rate (C), depth of cut (D) and insole design type (F), while the EVA foam rubber hardness factor (E) is set at Level 1. Therefore, two cutting parameter optimal conditions for minimal Ra (orthotics shoe insole for Patients 1 and Patient 2 suffering from diabetes) can be simplified according to a combination of factors, A_2 B_3 C_1 D_2 E_1 F_2 (Table 3). The optimal setting parameter A_i B_1 C_1 D_2 E_1 F_2 (Table 4) meant Level 1 for toolpath strategy (A); Level 3 for spindle speed (B), feed rate (C), depth of cut (D), as well as the type of EVA rubber foam (E); and Level 2 for the insole design (F). The results of this combination are presented in Tables (3)-(4), where the means and the SNR values with the quality characteristic of the Taguchi method are smaller, it can be proved better in this paper. The values of contributions (%) for the response Ra (insole for Patient 1 and Patient 2) respectively is 78.62% and 89.00% (with error 21.376% and 11.00%), while for the working time it is 99.98% and 100% on ANOVA (analysis of variance) in Tables (5)-(6). Furthermore, the percentage contribution to the linear model,
the square model, and the interaction between factors on Patient 1 of the Ra in Table 5 is 37.05% (linear), 15.24% (squares), and 15.13% (interaction between factors). Factor E and F contribute more significantly (17.20% and 17.04%), followed by Factor C (1.73%), B (1.21%), D (0.95%), and A (0.42%). Similarly, the ANOVA values for Ra for Patient 2 give the result that Factor C is the most effective factor, contributing 6.54%, followed by Factor F (2.29%), D (1.27%), E (0.59%), B (0.30%), and A (0.22%) are shown in Table 6. Correspondingly, Ra of the lowest orthotic shoe insole can be achieved by an optimum condition milling process (factors feed rate and the type of material EVA foam rubber), and also by the results of research work has been published [4, 11-12].

Table 5 ANOVA for surface roughness Ra for Patient 1

| Variation of Source | DoF | SS     | MS     | F-value | P-value | Contribution (%) |
|---------------------|-----|--------|--------|---------|----------|------------------|
| Model               | 13  | 6.353  | 0.4887 | 3.68    | 0.013    | 78.62            |
| Linear              | 6   | 2.994  | 0.4990 | 3.76    | 0.022    | 37.05            |
| A                   | 1   | 0.034  | 0.0339 | 0.26    | 0.406    | 0.42             |
| B                   | 1   | 0.098  | 0.0979 | 0.74    | 0.538    | 1.21             |
| C                   | 1   | 0.140  | 0.1402 | 1.05    | 0.323    | 1.73             |
| D                   | 1   | 0.077  | 0.0771 | 0.58    | 0.460    | 0.95             |
| E                   | 1   | 1.390  | 1.3901 | 10.5    | 0.007    | 17.20            |
| F                   | 1   | 1.377  | 1.3768 | 10.4    | 0.007    | 17.04            |
| Square              | 2   | 1.232  | 0.6159 | 4.63    | 0.03     | 15.24            |
| C*C                 | 1   | 0.839  | 0.839  | 6.31    | 0.026    | 10.38            |
| E*E                 | 1   | 0.393  | 0.3930 | 2.96    | 0.109    | 4.86             |
| 2-Way Interaction   | 7   | 1.223  | 0.2791 | 2.1     | 0.130    | 15.13            |
| A*B                 | 1   | 0.127  | 0.127  | 0.96    | 0.346    | 1.57             |
| A*C                 | 1   | 0.209  | 0.0033 | 2.19    | 0.163    | 3.59             |
| B*F                 | 1   | 0.264  | 0.2638 | 1.99    | 0.182    | 3.26             |
| C*D                 | 1   | 0.509  | 0.5086 | 3.83    | 0.072    | 6.29             |
| D*F                 | 1   | 1.068  | 1.068  | 8.04    | 0.014    | 13.21            |
| Error               | 13  | 1.727  | 0.1329 |         |          | 21.376           |
| Total               | 26  | 8.081  |        |         |          | 100              |

Table 6 ANOVA for surface roughness Ra for Patient 2

| Variation of Source | DoF | SS     | MS     | F-value | P-value | Contribution (%) |
|---------------------|-----|--------|--------|---------|----------|------------------|
| Model               | 16  | 8.8423 | 0.5526 | 5.06    | 0.049    | 89.00            |
| Linear              | 6   | 1.1329 | 0.1882 | 1.73    | 0.212    | 11.40            |
| A                   | 1   | 0.0214 | 0.0214 | 0.2     | 0.668    | 0.22             |
| B                   | 1   | 0.0299 | 0.0299 | 0.27    | 0.612    | 0.30             |
| C                   | 1   | 0.6500 | 0.6501 | 5.95    | 0.035    | 6.54             |
| D                   | 1   | 0.1258 | 0.1258 | 1.15    | 0.309    | 1.27             |
| E                   | 1   | 0.0588 | 0.0588 | 0.54    | 0.480    | 0.59             |
| F                   | 1   | 0.2274 | 0.2274 | 2.08    | 0.180    | 2.29             |
| Square              | 3   | 4.7855 | 1.5952 | 14.6    | 0.001    | 48.17            |
| A*A                 | 1   | 1.4859 | 1.4859 | 13.6    | 0.004    | 14.96            |
| D*D                 | 1   | 0.1969 | 0.1969 | 1.8     | 0.209    | 1.98             |
| E*E                 | 1   | 2.5920 | 2.5920 | 23.73   | 0.001    | 26.09            |
| 2-Way Interaction   | 7   | 3.09987| 0.44284| 4.05    | 0.023    | 31.20            |
| A*F                 | 1   | 1.15284| 1.15284| 10.55   | 0.009    | 11.60            |
| B*E                 | 1   | 0.2085 | 0.2085 | 1.91    | 0.197    | 2.10             |
| B*F                 | 1   | 0.2170 | 0.2170 | 1.99    | 0.189    | 2.18             |
| C*D                 | 1   | 0.3737 | 0.3737 | 3.42    | 0.094    | 3.76             |
| D*F                 | 1   | 0.2452 | 0.2452 | 2.24    | 0.165    | 2.47             |
| E*F                 | 1   | 0.29503| 0.29503| 2.7     | 0.131    | 2.97             |
| Error               | 10  | 1.092  | 0.1093 |         |          | 11.00            |
| Total               | 26  | 9.935  |        |         |          | 100.00           |
RSM was conducted in this paper for modeling and analyzing several variables that have a significant relationship between the dependent variable and one or more of the independent variables defined in the study. In this way, the experimental results of the EVA foam rubber milling process in CNC machines can be developed into a mathematical model with response Ra and Ta. The second-order regression model can be seen in Eqs. (1)-(4). This regression model is a function of six machining parameter variables (A, B, C, D, E, and F), which were set in Table 1, and can be expressed using RSM with Minitab software v17.

\[
Ra_{(patient 2)} = 77.983 + 0.39A - 0.0186B + 0.133C + 134.941D - 8.016E - 0.217F \\
+ 0.0000119AB + 0.000679AC - 2.623AD + 0.0758AE - 0.325AF + 0.0000056BC \\
- 0.0039BD + 0.000217BE + 0.000368BF - 0.104CD + 0.00532CE - 0.00508CF \\
+ 0.1501DE + 13.582DF - 0.199EF - 0.1005A^2 + 0.00000049B^2 - 0.00012C^2 \\
+ 13.39D^2 + 0.069E^2 - 1.436F^2
\]

(1)

\[
Ra_{(patient 1)} = -104.433 - 0.155A + 0.0058B + 0.1403C + 168.123D + 0.726E + 1.104F \\
+ 0.000071AB - 0.00093AC + 1.682AD + 0.2AE + 0.0754AF - 0.00000116BC \\
- 0.00445BD - 0.0000678BE - 0.00025BF - 0.0785CD - 0.000984CE \\
- 0.0123CF - 1.245DE - 8.659DF + 0.27EF - 0.2548A - 0.2548A^2 \\
- 0.00000072B^2 - 0.000063C^2 - 69.614D^2 + 0.0504E^2 - 3.76F^2
\]

(2)

\[
Ta_{(patient 1)} = 5604.97 - 3.03A^2 - 0.000002B^2 + 0.00203C^2 + 4157.03D^2 + 0.017E^2 + 103.08F^2 \\
- 97.395A - 0.25B - 8.18C + 85.5D + 1.36E - 27.33F + 0.015AB - 0.0163AC \\
+ 75.275AD + 0.083AE + 22.35AF + 0.00038BC - 0.13BD + 0.00019BE - 0.011BF \\
- 0.651CD - 0.006CE - 0.006CF - 3.146DE + 226.42DF + 0.085EF
\]

(3)

\[
Ta_{(patient 2)} = 2749.34 - 6.4279A^2 - 0.0000037B^2 + 0.00176C^2 + 319.05D^2 + 0.0015E^2 + 133.45F^2 \\
+ 175.74A - 0.0507B - 6.125C + 2678.92D + 0.235E + 119.739F + 0.00107AB - 0.22AC \\
+ 32.8AD + 0.0775AE + 21.92AF + 0.00026BC - 0.227BD + 0.00018BE - 0.0132BF \\
+ 0.178CD - 0.002CE - 0.35CF - 7.51DE + 549.02DF + 0.471FE
\]

(4)

In this study, the response to Ra in both patients provides R2 of 97.80% (Patient 1) and 98.20% (Patient 2). In this case, the value of R2 was close to 100%, as desired for this experiment. Therefore, the two regression models that were formed above can be used to predict the Ra at certain design parameters.

For a better understanding of the interaction effect of all the machining variables on Ra, 3D-plot curves for the measured response can be developed using Eqs. (1)-(4). The 3D surface graphs illustrate the relationship between cutting parameters and the response Ra is shown in Figs. (4)-(5).

The predictability of the mathematical model developed by researchers was performed separately for each experiment, which provides the optimum Ra value for each insole right leg and left leg at 8.538 μm and 7.828 μm, respectively. The optimal Ra value has been obtained precisely and significantly to the optimal cutting conditions that have been set: toolpath strategy (raster machining 45°), spindle speed (14,500 rpm), feed rate (850 mm / min), step over (0.25 mm), EVA foam with hardness 20-35 HRc (Level 1), and the type of insole design with wide tolerance set on 0.75 mm. At these conditions, the value of Ra is predicted to follow a trend that is similar to the experimental value in the manufacturing process in the CNC milling machine with an average absolute percentage error for the second insole less than 3.6% (Tables 7-8) [11-13].
Fig. 4 The 3D plot curve of surface roughness (Ra)

(a) Spindle feed-toolpath strategy for left foot of patient no. 1
(b) Spindle feed-toolpath strategy for right foot of patient no. 1
(c) Type material-feeding for left foot of patient no. 2
(d) Type wide tolerance-type of material for right foot of patient no. 2

Fig. 5 The 3D plot curve of Time machining (Ta)

(a) Type EVA foam-Toolpath for left foot of patient no. 1
(b) Type design insole-Type EVA foam for right foot of patient no. 1
(c) Type EVA foam-Toolpath for left foot of patient no. 2
(d) Design insole-type Type EVA foam for right foot of patient no. 2
In this approach, the measured parameter of each predicted response can be transformed into a dimensionless desirability value \( d_F \) \[14\]. The scale of the desirability function is between 0 and 1. If the value of \( d_F = 0 \) or close to 0, the response is considered to be unacceptable. If the value of \( d_F = 1 \) or close to 1, the response is considered to be optimal.

A confirmation experiment was performed at the optimum conditions predicted and yielded Ra values of 8.432 μm and 7.557 μm (insole for Patient 1 and Patient 2, respectively) as well as Tm values of 213.89 min. and 229.80 min. (Table 7). The ability to successfully predict from the model also tested in optimal conditions. The predictive values of Ra = 8.538 μm and 7.828 μm were obtained from the model (Table 8). Optimal results obtained with different optimization techniques (TM and TM-RSM) were compared and there was a significant improvement in the surface which was finished with the hybrid approach. Predictive and comparative analyses of optimal conditions in this study are all summarized in Table 7. Based on the observations in Table 8, the hybrid approach of optimization techniques with TM-RSM provided 0.24% and 1.56% improvement of the surface finishing process for the same shoe orthotics insole compared with the optimal results obtained from the TM approach. The TM-RSM hybrid approach provides significant values for the absolute error of shoe orthotic insoles for the left leg and right foot for both patients with diabetes mellitus, 11.31%, and 4.85%, respectively the desirability function for the Ra shoe orthotic insoles of the left leg and right for both the patients are presented in Fig. 6.

Table 7 Optimum parameters and test results confirm the experimental results with predicted Ra and Ta values using the response surface method (RSM)

| Optimal Cutting Parameters Conditions | Toolpath | Spindle Speed (RPM) | Feed Rate (mm/min) | Step Over (mm) | Type of Material EVA | Width Tolerance (mm) | Ra_Based (μm) | Percentage Error (%) |
|----------------------------------------|----------|---------------------|--------------------|----------------|----------------------|---------------------|---------------|----------------------|
| A_1B_2C_3D_4E_5F_2                     | raster   | 15,000              | 900                | 0.3            | EVA                  | 0.75                | 213.89        | 216.56               | 1.25                |
| A_1B_2C_3D_4E_5F_2                     | raster   | 15,000              | 900                | 0.3            | EVA                  | 0.75                | 229.80        | 237.36               | 3.29                |
| A_2B_3C_2D_3E_2F_3                     | raster   | 14,500              | 850                | 0.25           | EVA                  | 20–35               | 7.557         | 7.828               | 3.59                |
| A_2B_3C_2D_3E_2F_3                     | raster   | 14,500              | 850                | 0.25           | EVA                  | 20–35               | 8.432         | 8.538               | 1.26                |

Table 8 Comparison of Ra optimum and experimental results

| Optimization techniques | Ra | | | | | | | | |
|------------------------|----|----|----|----|----|----|----|----|----|
|                         | Optimal | predicted | Patient 1 | Patient 2 | Patient 1 | Patient 2 | Absolute % error | Patient 1 | Patient 2 |
| Taguchi Approach (TM)   | 7.554 | 7.332 | 6.936 | 6.752 | 8.18 | 7.68 |
| Approach TM-RSM         | 7.572 | 7.448 | 8.538 | 7.828 | 11.31 | 4.85 |
| Percentage (%) improvement | 0.24 | 1.56 | - | - |

| Optimization techniques | Ta | | | | | | | | |
|------------------------|----|----|----|----|----|----|----|----|----|
|                         | Optimal | predicted | Patient 1 | Patient 2 | Patient 1 | Patient 2 | Absolute % error | Patient 1 | Patient 2 |
| Taguchi Approach (TM)   | 213.89 | 229.8 | 179.04 | 212.46 | 16.29 | 7.55 |
| Approach TM-RSM         | 276.63 | 286.17 | 217 | 237.36 | 21.71 | 17.06 |
| Percentage (%) improvement | 22.68 | 19.70 | - | - |
In the study, the desirability functions $T_a$ was selected as "the smaller the better" because the optimal minimum $T_a$ can be achieved in the machining parameters in the optimum CNC milling machine. The desirability functions of "the smaller the better" can be shown in Fig. 6, the patient's optimal value, $T_a1$, in the model was reached at 309.22 minutes, which gives a chance to the toolpath 2.09 (Levels 2–3), 14075.39 rpm spindle speed (Level 1), 936.88 mm/min feed rate (Level 3), 0.28 mm step over (Level 3), a material with hardness 76.67 HRc (Level 3), and the 0.82 design (Level 3). The optimal value for model $T_a2$ patients was achieved at 286.098 minutes and was set at 2.15 (Levels 2–3), 14935.86 rpm spindle speed (Level 3), 859.88 mm/min feed rate (Level 3), 0.23 mm step over (Level 2), a material with hardness 11.01 HRc (level 1), and 0.75 design type (Level 2). The $T_a$ desirability values for both patients reached values of 1.00. As a result, the response is considered perfect for the target value. The results of this paper had been proven by researchers [6–7, 15–16] in the process of design, manufacturing, and fabricating orthotic shoes comprising shoe last, the shoe insole and, special orthotics for diabetes patients.

(a) Surface roughness (Ra)

(b) Machining time ($T_a$)

Fig. 6 Profile predicted values and desirability with TM-RSM hybrid methods

(D=composite desirability; d= individual desirability; High = highest value parameter; Cur = optimal current value of control parameter; Low = lowest value parameter, $y$ = response parameter, $Ra$ = average surface roughness; $A$ = toolpath strategy; $B$= spindle speed; $C$= feed rate; $D$ = step over; $E$ = EVA foams with variable hardness; $F$ = typical design of insoles with wide tolerance)
4. Conclusion

In this research, a TM_RSM approach was successfully implemented to create a mathematical model and optimize the milling process for ISO diabetes made of EVA foam rubber in a CNC milling machine. Based on the discussion mentioned earlier, the conclusions can be drawn as follows:

1. Ra at optimum cutting conditions based on the TM approach shows an optimum insole Ra value of 6.936 μm for Patient 1 and 6.752 μm for Patient 2. The optimal combination is in Position A₂B₁C₁D₂E₁F₂ and A₂B₂C₂D₂E₁F₂.

2. The optimum cutting conditions RSM-based approach shows the value of the surface roughness was Ra = 7.828 μm (Patient 1) and Ra = 8.538 μm (Patient 2), both were under the cutting parameters in A₂B₂C₂D₂E₁F₂.

3. The TM-RSM-based hybrid approach produces optimal machining parameter conditions at position: toolpath strategy (raster 45° and step & shallow machining), spindle speed (14,500–15,000 rpm), feed rate (800–900 mm / min), step over is 0.3 mm, the hardness of EVA foam material (20-35 HRc and 50-60 HRc), and ISO diabetes tolerance range (0.50 to 0.75 mm). The Ra optimum value of each was predicted at Ra = 7.572 μm and 7.648 μm for the insole left leg and right leg, respectively.

4. The surface quality for the TM-RSM hybrid method is better than the other methods (0.24% for left foot insole and 4.13% for right foot insole) when compared to the optimum value of the Taguchi method.

5. Both methods (TM approach and TM-RSM approach) are very beneficial for data optimization of the results of CNC milling machine operation, which aims to reduce the time and cost of manufacture, to produce orthotic shoe insoles for a patient with diabetes.

Acknowledgment

We would like to gratefully thank you for PUTP Polytechnic ATMI Surakarta, Tribology Laboratory of the Department of Mechanical Engineering, University of Diponegoro in Semarang and CV EMA Pacific Surakarta that already provide full support in the form of infrastructure support CAM, CAD, and RE during the design, developed process as well as the writing of this paper.

This research was funded by Directorate of Research and Community Service, Directorate General of Research and Development Strengthening, Ministry of Research, Technology and Higher Education Fiscal Year 2019, grant Number: 257-93/UN7.P4.3/PP/2019 and Number: 257-73/UN7.P4.3/PP/2019. Letter of agreement for the implementation of research acceleration grants at the Atma Jaya University Yogyakarta, Number: 382/HB-PEN PGB/LPPM/XI/2019.

Conflicts of Interest

The authors declare no conflict of interest.

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