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CNC milling of EVA foam with varying hardness for custom orthotic shoe insoles and process parameter optimization

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ABSTRACT

CNC milling strategy of EVA foam with varying hardness to provide a high degree of surface roughness of orthotic shoe insoles is presented in this work. Machining parameters (spindle speed, feed rate, tool path strategy, and step over) in addition to hardness material and wide tolerance insoles were optimized using a hybrid approach of Taguchi-Response Surface Methods (TM-RSM). The aim of this exploration was to develop mathematical models and determine the optimum machining parameters which could be applied for the CNC milling of EVA foam as the insoles. The research was implemented on the CNC milling machine with a standard milling cutter and run under dry coolants. The outcomes of the six parameters on the average values of surface roughness were initially analyzed by an S/N ratio of TM. Optimal conditions were established from the TM and then used to determine the optimum values in RSM modeling. The final results indicate the significant improvement of percentages (0.24% and 4.13%) in the surface roughness of the insoles obtained with TM-RSM as compared to the TM analysis. It is envisaged the present study would add to the understanding of production for orthotic shoe insoles through CNC milling.

Keywords: EVA foam; CNC milling; RSM; Taguchi; surface roughness; optimization.

INTRODUCTION

EVA (Ethylene-Vinyl Acetate) foam has many applications in sports and medical engineering because of their excellent properties including good energy-absorber and high fracture toughness relative to other polymers [1]. EVA foam in sports application is typically layered with harder polymers such as polycarbonate or a composite laminate to provide an excellent performance in dumping property. Moreover, EVA foam is consistently used in advanced composites for special applications of orthotic shoe insoles. Consequently, this material is gaining wide acceptance in the footwear industry sector, because of providing lighter weight shoes along with high comfort, resiliency, and durability [1].

Among all polymers employed as the footwear, EVA foam is effective as foot orthotics insoles for prevention of the foot pain [2], including foot ulcer which is a common and harmful problem of diabetes [3, 4]. Foot ulcers are the main cause of increasing the risk of foot infection and amputation. Therefore, these conditions may reduce the healthiness associated to life quality and significantly increases in the prices of foot caution [5]. In this way, the diabetic foot could be treated by wearing custom-made insoles, which can reduce the mechanical load upon the plantar foot ulceration during walking [6, 7]. Correspondingly, the product design, hardness property of EVA foam, and fitting of the orthotic insoles are the primary factors influencing the foot-insole interface pressures, the comfort of walking, and eventually, the effectiveness of the foot orthotics treatment [8].

Further, large differences in insole hardness may influence on the perceptual and biomechanical variables, when a diabetic patient experienced shock and impact loads. Therefore, an extensive research was performed to reduce this main factor by varying insole hardness and different feature of shoe constructions. These goals can only be achieved if an effort in developing product design of orthotic shoe insoles uses an appropriate manufacturing process, which can maintain the high production efficiency [9].

Currently, the orthotic insoles can be prescribed and made using footprints in a foam box. Nevertheless, this method is not capable to make insoles with high precision and accuracy when assembled with the patient's foot geometry, hence producing the orthotic footwear with a low comfort. Moreover, this manual method results in higher production cost and time [10]. With the rapid development of computer-aided design (CAD) technology, three-dimensional (3D) design of orthotic insoles can be made for various foot contours with providing the best fitting of the orthotic insoles and reducing production cost and design phase [11. Additionally, the accessibility of a reverse engineering (RE) and a reverse innovative design (RID) provides the rapid production of insoles with accuracy and precision in size dimension [7, 12-13]. Here contour of the foot abnormalities can be scanned by a 3D scanner providing an accurate data of the 3D mesh, which can subsequently be used in a subtractive manufacturing process of insoles (either adaptive manufacturing using a 3D printer machine or a CNC milling machine) by [14, 15].

Further, the use of the 3D-foot scanning system, CAD and CAM (computer-aided manufacturing) for fabricating molds and custom-made orthotics apparatuses become suitable and cost-effective method [7, 16]. Consequently, the broad varieties of insole designs can be fabricated for the diabetic foot requirements. The 3D printing has been applied in CAM of an ankle-foot orthosis (AFO) yielding the AFO product with better dimensional accuracy [17-19]. This desired manufacturing step may produce orthotic insoles with the best fitting for foot patient with diabetes [7, 16, 20-21]**.** This need is further strengthened by determining of machining strategy which requires certain cutting parameters for yielding the acceptable surface roughness.

Correspondingly, more efficient and rapid manufacturing of bespoke products such as orthotic insoles can be acquired by CNC machining, which is preferred to pieces (unit) or smaller number production. This manufacturing method enables simple and scalable of fabrication of insoles with the best fitting. However, machining of EVA foam as orthotic insoles is a challenging process from the point of machinability because the material has anisotropic and non-homogeneous properties [1]. Unlike metal machining, the cutting of

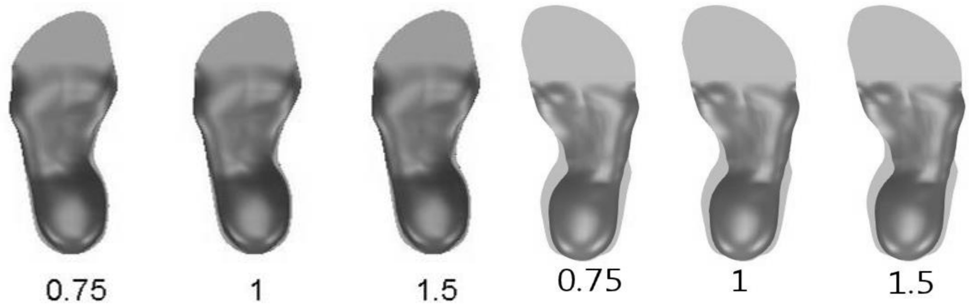
EVA foam occurs on compressive shearing and fracture. This puts stringent requirements on the selection of machining parameters and the cutting material.

In summary, in order to complement the previous findings, the complete analysis of machining parameters, optimization and their effect on surface quality (the surface roughness) is required to provide custom-made insoles for effective offloading the foot and anticipation of foot ulcers. The optimization of the cutting parameters in CNC machining of EVA foam with varying hardness is needed to complete quality data about the insole product, which would be characterized by the perception and biomechanical variables related to the pain prevention and comfort, whereas in that respect is no report on the optimization of the cutting parameters in CNC machining of EVA foam with varying hardness. Therefore, the objective of this paper is firstly, to experimentally investigate the process parameters to obtain the desired roughness surface, and secondly, to improve the mathematic model and process parameter optimization (spindle speed, tool path strategy, feed rate, step over, EVA foam with variable hardness and typical design of insoles with wider tolerance) using the hybrid approach of the TM-RSM. This hybrid approach was selected for improving a mathematic model and optimizing the cutting parameters of the orthotic insoles in the CNC milling of EVA foam. In this study, the optimum conditions of cutting parameters in CNC milling, the best level of hardness in EVA foam, and the optimal typical design of insoles with wider tolerance were obtained through the second order regression model and plot for the 3D curve of response data versus all contributing factors.

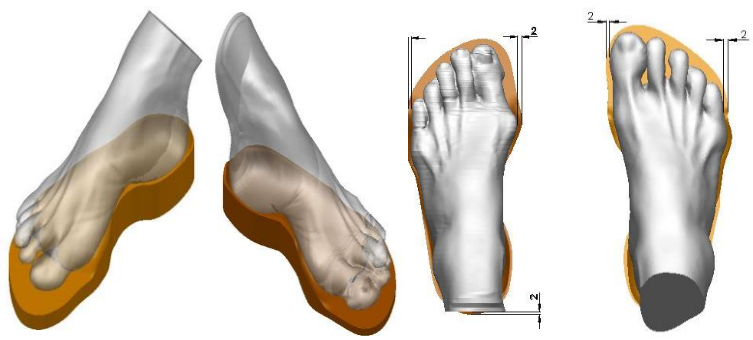
METHODS AND MATERIALS

3D Designing of Orthotic Insoles

Three types of orthotics insole design that fits the contour of the diabetic foot were manufactured in the CNC milling. The RID method was used to develop the 3D models of insoles with the help of 3D scanning, of which the base curve surface modeling of three insole design could be explored using the software (PowerSHAPE 2016) according to [11]. The design results for a wide tolerance of the insole along X-Y axes (0.50-1.00 mm) are presented in Figure 1. Obviously, the usage of RID technique provided the insole model having a good accuracy in dimensions.



(a) Top view of 3D CAD model of insole with wide tolerance acrros axis XY from 0.5 to 1.00 mm



(b) Top view tolerance 0.75 mm of insole shoe orthotic

Figure 1. The 3D CAD model of insole shoe orthotics.

Cutting Conditions and Experimental Design

There was machining parameters evaluated, including tool path strategy (A Factor), spindle speed (B Factor), feed rate (C Factor), step over (D Factor), EVA foam with variable hardness (Factor "E") and design of insoles with wider tolerance (Factor "F"). The cutting parameters level were designated following to the cutting tools and CNC milling specifications (Table 1). The experimental design consisted of six parameters and three levels selected according to the Taguchi's $L_{27}3^6$ as orthogonal arrays (OA) and are given in Tables 2 and 3. The OA in the Taguchi method, matrix was chosen as an efficient average to perform the research with the minimum number of experiments. The Taguchi method also used the S/N ratio to analyze the effects of contributing factors on the responses. There are three S/N ratio's characteristics; the "lowest is the best", the "highest the best", and the "highest nominal is the best" in the process parameter optimization. In this research the arithmetic mean of surface roughness (Ra) and the average of the maximum value of the profile (Rz) in the optimal conditions were studied by the ratio as follows [22, 23] :

$$\text{SN ratio} = -10\log\frac{1}{n}(y_1^2 + y_2^2 + y_3^2 + ... + y_n^2) \quad (1)$$

where variable y_1, y_2, y_3, and yn are the responses of the machining process for a test condition that repeated n times. The S/N ratios were calculated using Equation (1) for 27 experimental trials and the results are provided in Table 4.

Table 1. The parameters of machining and level experiment.

Factor	Level		
	1	2	3
A	Raster	Raster 45^{O}	Step and Shallow
B	14000 rpm	14500 rpm	15000 rpm
C	800 mm/min	850 mm/min	900 mm/min
D	0.20 mm	0.25 mm	0.30 mm
E	20-35 HRc ($31/sheet)	40-50 HRc ($37/sheet)	50-60 HRc ($47/sheet)
F	0.50 mm	0.75 mm	1.00 mm

Table 2. Design matrix of orthogonal array $L_{27}3^6$ for the experimental runs.

No Experiment	Factor A	Factor B	Factor C	Factor D	Factor E	Factor F
1	1	1	1	1	1	1
2	1	1	1	1	2	2
3	1	1	1	1	3	3
4	1	2	2	2	1	1
5	1	2	2	2	2	2
6	1	2	2	2	3	3
7	1	3	3	3	1	1
8	1	3	3	3	2	2
9	1	3	3	3	3	3
10	2	1	2	3	1	2
11	2	1	2	3	2	3
12	2	1	2	3	3	1
13	2	2	3	1	1	2
14	2	2	3	1	2	3
15	2	2	3	1	3	1
16	2	3	1	2	1	2
17	2	3	1	2	2	3
18	2	3	1	2	3	1
19	3	1	3	2	1	3
20	3	1	3	2	2	1
21	3	1	3	2	3	2
22	3	2	1	3	1	3
23	3	2	1	3	2	1
24	3	2	1	3	3	2
25	3	3	2	1	1	3
26	3	3	2	1	2	1
27	3	3	2	1	3	2

Experimental outcomes of the 27 trials and the surface roughness mean for the orthotic shoe insole gauged by surface roughness tester (Mark Surf PS 1) are given in Table 3.

Table 3. Surface roughness Ra (the left and the right foot insoles).

No exp	Uncoded value of factor						Ra left foot insole	Ra right foot insole
	A	B	C	D	E	F	µm	µm
1	1	1	1	1	1	1	7.671	8.594
2	1	1	1	1	2	2	8.995	9.436
3	1	1	1	1	3	3	9.252	8.081
4	1	2	2	2	1	1	6.969	7.716
5	1	2	2	2	2	2	8.011	8.800
6	1	2	2	2	3	3	8.368	6.618
7	1	3	3	3	1	1	7.812	8.027
8	1	3	3	3	2	2	8.324	9.286
9	1	3	3	3	3	3	8.527	8,319
10	2	1	2	3	1	2	7.162	7,881
11	2	1	2	3	2	3	8.198	9,225
12	2	1	2	3	3	1	8.080	7,496
13	2	2	3	1	1	2	7.967	8,395
14	2	2	3	1	2	3	9.330	8.771
15	2	2	3	1	3	1	7,659	8.897
16	**2**	**3**	**1**	**2**	**1**	**2**	**8.432**	**7.557**
17	2	3	1	2	2	3	7.934	7.361
18	2	3	1	2	3	1	8.417	6.890
19	3	1	3	2	1	3	7.963	8.151
20	3	1	3	2	2	1	8.588	9.061
21	3	1	3	2	3	2	8.822	7.970
22	3	2	1	3	1	3	8.165	7.983
23	3	2	1	3	2	1	7.974	7.881
24	3	2	1	3	3	2	7.554	8.047
25	3	3	2	1	1	3	8.009	6.850
26	3	3	2	1	2	1	7.599	8.489
27	3	3	2	1	3	2	8.372	9.008

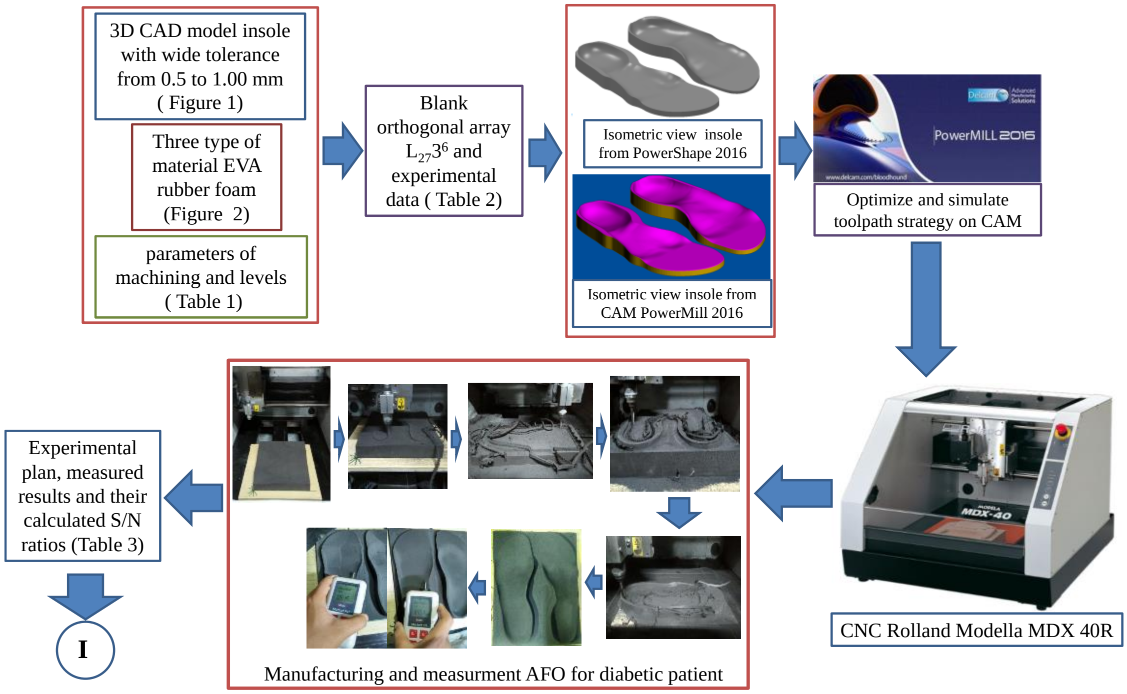
Table 4. Response value for S/N ratios (dB) and means of effect.

Control factor	Surface roughness Ra (the left foot insole)					Surface roughness Ra (the right foot insole)				
	Level 1	Level 2	Level 3	SN Ra	Delta	Level 1	Level 2	Level 3	SN Ra	Delta
	Mean (μm)			(dB)	(μm)	Mean ((μm)			(dB)	(μm)
A	8,214	**8.095**	8.131	26618.0	0.119	8.320	**8.053**	8.181	5637.1	0.267
B	8.304	8.158	**8.011**	4664.21	0.293	8.433	**7.976**	8.123	1848.7	0.456
C	**7.863**	8.277	8.332	1517.19	0.469	8.009	**7.981**	8.542	1004.9	0.561
D	8.317	**7.989**	8.167	3692.73	0.328	8.502	**7.791**	8.238	776.7	0.711
E	**7.794**	8.328	8.350	1007.68	0.556	**7.906**	8.701	7.925	487.28	0.795
F	8.193	**7.863**	8.443	1182.39	0.580	8.117	**7.932**	8.486	1260	0.554

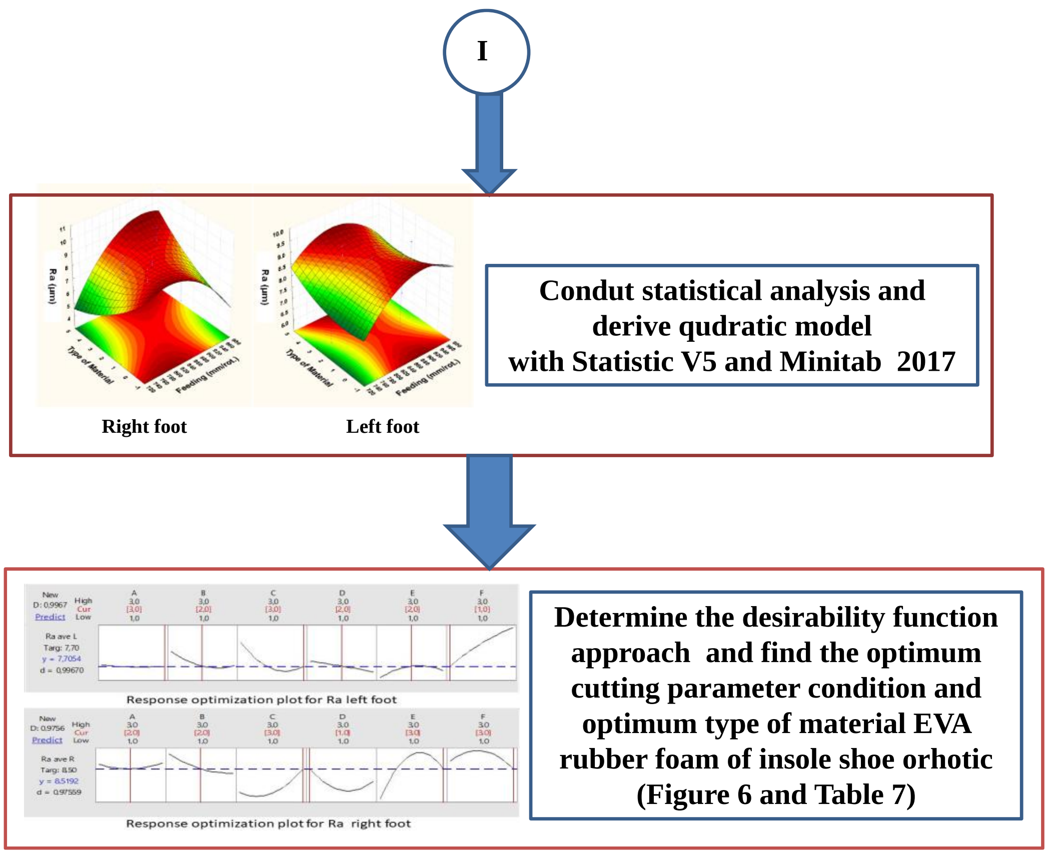
Workpiece Materials, Machine Tools and Cutting Tool Specifications

EVA foam with sizes of 250 x 95 x 23 mm in thickness were machined in the CNC milling experiments. The hardness of the material in the range of 20-60 HRC was measured using the Shore Hardness Tester (Asker CL-150). Three types of EVA foam were identified according to the three levels of hardness (level 1 of 20-35 HRC, level 2 of 35-45 HRC and level 3 of 50-60 HRC). Based on the price data of EVA foam in the local market of Jakarta, Indonesia, materials by the size of 1200 x 2400 x30 mm exists on the price range: $31.00/sheet (Factor E, level 1), $37.00 /sheet (Factor E, level 2), and $47.00/sheet (Factor E, level 3). In addition, EVA foam density is 55–65 kg/m^3, the nominal size of 2000 x1000 mm, a nominal split thickness 3–36 mm, tensile strength is 800 kPa and tear strength material is 4.5 kN/m [24].

The milling tests of EVA foam were performed by a milling machine [Rolland Modella MDX40R CNC] that is equipped with a maximum spindle rotation of 16000 rpm, and spindle speed motor DC of brushless motor with power of 100 W. The cutting tool used was a carbide tool with type of end milling [SECO, with specification 93060F] and ball-nose of cutter milling [JS533060D1B0Z3-NXT]. The surface roughness (Ra) was measured by the tester with tolerance 0.001 mm at three point locations. The cutoff length of 5 mm was selected, while the surface roughness measurements were performed at three times for each milled surface. The average roughness values (Ra) (the left and the right foot insoles) for each machining experiments are given in Table 3. The stages of this research are presented in Figure 2, while the resulting product of insoles is given in Figure 3.



(a)



(b)

Figure 2. A schematic diagram of this research: (a) Experimental; (b) Modeling.

Figure 3. Research output: (a) Product insoles of EVA foam with different hardness, (b) confirmation insole product with 3D prototype foot of patient with diabetic.

Mathematical Modeling of RSM Method

RSM was the combination of statistics and mathematical procedures that utilize the system modeling and problem analysis to create a response of interest. This response is effected by several variable and the target value [25]. The first stage in RSM is finding the appropriate estimation of the true function between the y value and the set of independent variable (x_i). When a linear function is obtained, then the approximating function is the first-order model (Equation 2):

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k + \varepsilon \tag{2}$$

where, β_0 = constant, β_k = regression coefficient, x_1 = input parameters and ε = error.
However, the polynomial function of the second-order model is commonly recommended because the first order of the model has the highest lack-of fit. Here, the second order RSM model can be expressed as:

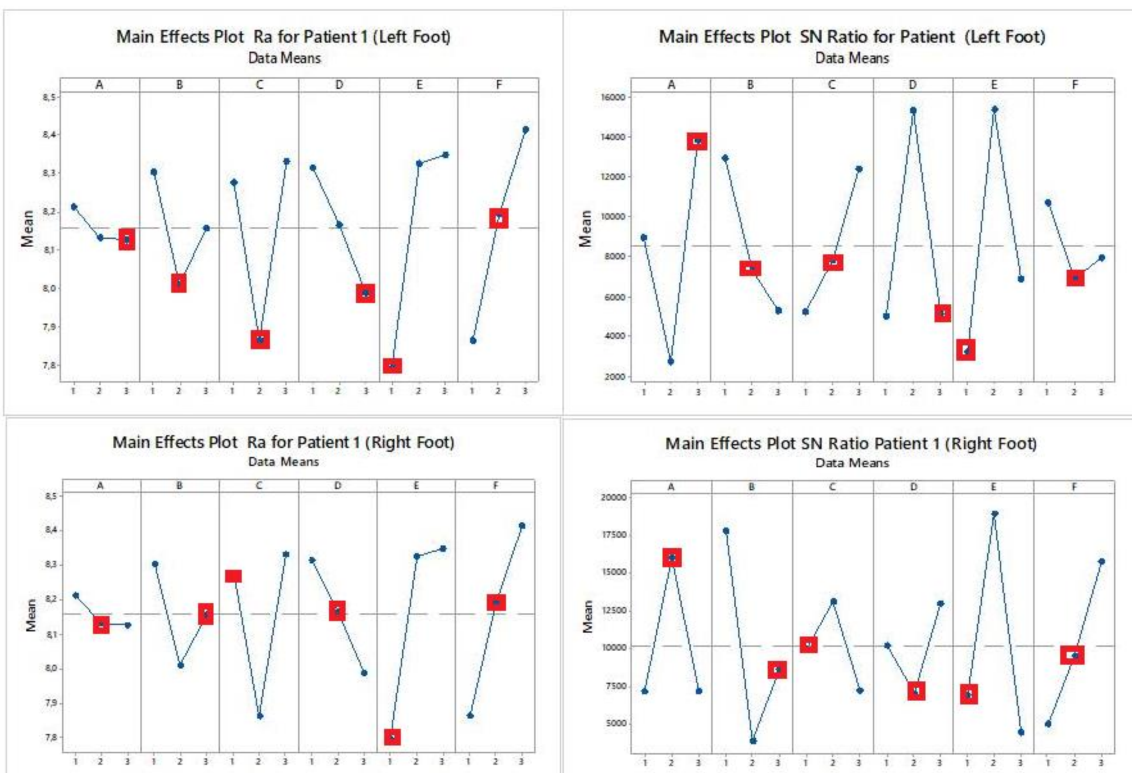
$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum \sum_{i<j}^{\infty} \beta_{ij} x_i x_j + \varepsilon \tag{3}$$

Moreover, the value of each coefficient and constant was computed by the least-square method. Finally, the desirability function (dF) can be used to optimize of multiple-response TM-RSM [26].

RESULT AND DISCUSSION

Analysis of S/N Ratio

In this work, the Ra values was got from the experimental runs performed on the selection of cutting parameters are shown in Table 3. The each factor level effects on the quality features were examined using the S/N ratio. The difference value S/N ratio between maximum and minimum (main effect) are also presented in Table 4. A low value of surface roughness (Ra) could be achieved by the optimum machining conditions, of which the cutting parameters and their levels for this experiment of the left foot insoles were obtained with the second level of toolpath strategy (A), depth of cut (D) and typical design of insoles (F), the first level of feed rate (C) and hardness of EVA foam (E), and third level of spindle speed (B). For surface roughness (Ra) of the right foot insoles, the levels that ensure the machining would be in the target value are level 2 of the tool path strategy (A), spindle speed (B), feed rate (C), depth of cut (D) and typical design of the insole (F), and level 1 of the hardness of EVA foam (E). Therefore, two conditions of the optimum cutting parameters for the minimum surface roughness Ra (the left and right foot insoles) were simplified according to the combined factors of $A_2B_3C_1D_2E_1F_2$ and $A_2B_2C_2D_2E_1F_2$ (Figure 4).



(a) (b)

Figure 4. Main effects plots; (a) eEffects of control factors for Ra (b) the average of S/N ratio for Ra.

Taguchi-Based Selection of the Optimum Cutting Condition

The interaction analysis in the S/N ratios shows that $A_2B_3C_1D_2E_1F_2$ and $A_2B_2C_2D_2E_1F_2$ are the optimal combinations for yielding Ra of the left and the right foot insoles respectively. In this case of the left foot insole machining, two factors in the S/N data analysis were found to be significant, that are feed rate and hardness materials. The lowest level of feed rate and hardness material are the most desired conditions for the achievement of minimum Ra for the left foot insoles. Moreover, milling of the low hardness of EVA foam favours producing the minimum Ra for the right foot insoles. Therefore, the predicted optimal surface roughness (Ra_{pred}) can be expressed as follows:

$$Ra_{pred} = T_{Ra\_\exp} + (\bar{A}_2 - T_{Ra\_\exp}) + (\bar{B}_3 - T_{Ra\_\exp}) + (\bar{C}_1 - T_{Ra\_\exp}) + (\bar{D}_2 - T_{Ra\_\exp}) + (\bar{E}_1 - T_{Ra\_\exp}) + (\bar{F}_2 - T_{Ra\_\exp}) \quad (4)$$

Where, $\bar{T}_{Ra\_\exp}$ = 8.1576 , $\bar{A}_2$ = 8.095, $\bar{B}_3$ = 8.011, C_1 = 7.863, $\bar{D}_2$ = 7.989, $\bar{E}_1$ = 7.794, $\bar{F}_2$ = 7.863 hence Ra_{pred} for the left foot insole = 8.1576 + (8.095 - 8.1576) + (8.011 - 8.1576) + (7.863 - 8.1576) + (7.989 - 8.1576) + (7.794 - 8.1576) + (7.863 - 8.1576) = 6.936 μm.

$$Ra_{pred} = T_{Ra\_\exp} + (\bar{A}_2 - T_{Ra\_\exp}) + (\bar{B}_2 - T_{Ra\_\exp}) + (\bar{C}_2 - T_{Ra\_\exp}) + (\bar{D}_2 - T_{Ra\_\exp}) + (\bar{E}_1 - T_{Ra\_\exp}) + (\bar{F}_2 - T_{Ra\_\exp}) \quad (5)$$

Where, T_{Ra_Exp} = 8.1774, $\bar{A}_2$ = 8.053, $\bar{B}_2$ = 7.976, C_2 = 7.981, $\bar{D}_2$ = 7.791, $\bar{E}_1$ = 7.906, $\bar{F}_2$ = 7.932 hence, Ra_{pred} for the right foot insole = 8.1774 + (8.053 - 8.1774) + (7.976 - 8.1774) + (7.981 -8.1774) + (7.906 - 8.1774) + (7.932 - 8.1774) = 6.752 μm.

A confidence interval value (CI) was used to verify the features of quality the result of the research. The confidence interval was the step to predict the optimal values that can be counted using the following equations [22, 27]:

$$CI = \sqrt{F_{\alpha, dofV_{error}} V_{error} \, x \left(\frac{1}{n_{eff}} \right)} \quad (6)$$

$$n_{eff} = \frac{\text{Number of experiment}}{1 + \text{total dof in items in used in estimate}} \quad (7)$$

The confidence interval of the surface roughness Ra_{pred} for the left foot insole as follows: $F_{0.05;1,26}$ = 4.23 (tabulated), V_{erorr} = 0.2259 (Table 5), and N_{eff} = 2.25. The CI_{Ra} = ± *0.652 μm*. The predictive mean of Ra is Ra_{pred} = 6.936 μm, $\left|Ra_{pred} - CI\right| \langle Ra_{pred} \langle \left|Ra_{pred} + CI\right|$ ie. 6.936 –0.652 μm < 6.936 μm < 6.939 + 0.652 μm, 6.311 μm < Ra_{pred} < 7.615μm.

The confidence interval of the surface roughness Ra_{pred} for the right foot insole as follows: $F_{0.05;1,26}$ = 4.23(tabulated), V_{erorr} = 0.208 (From Table 5. a), and N_{eff} = 2.25. Thus, CI_{Ra} = *0.625 μm.* The predictive mean of Ra_{pred} = 6.752 μm $\left|Ra_{pred} - CI\right| \langle Ra_{pred} \langle \left|Ra_{pred} + CI\right|$., ie. 6.752 – 0.625 μm < 6.752 μm < 6.752 + 0.625 μm, 6.127 μm < Ra_{pred} < 7.377 μm.

Table 5 presents the results of the confirmation experiments according to the optimum levels of the combined factors. Moreover, the confidence interval (CI) was calculated for minimum Ra (the left foot and the right foot insoles) to be 0.652 µm and 0.625 µm respectively. Obviously, the result confirmation test, conducted for the responses were obtained in the CI value with a 95%. In the case of milling the left foot insole, the system optimization Ra was reached that using the smallest value of feed rate and the relevant factor of lowest hardness materials. This result is according to previous work by [28]. However, the smallest target value of surface roughness in the right foot insole was obtained by machining EVA foam with the smallest hardness.

Table 5. Comparisons of results of the experimental and predicted values by Taguchi method.

Response	Confirmatory experiment result	Calculated value	Confidence Interval (CI)	Difference Ra_{exp}-Ra Ra_{cal}	Optimization
$Ra_{left\ foot}$ (µm)	Ra_{exp} = 7,554	Ra_{cal} = 6.936	CI_{Ra} = 0.652	0.518	0.518 < 0.652 Sucessful
$Ra_{right\ foot}$ (µm)	Ra_{exp} = 7,332	Ra_{cal} = 6.752	CI_{Ra} = 0.625	0.580	0.580 < 0.625 Sucessful

ANOVA in RSM Method

Analysis of variance (ANOVA) was used to test the significance of the regression model, and individual model coefficients of factors (toolpath strategy, spindle speed, feed rate, step over, the type of EVA foam, and width of tolerance design) contributed to the surface roughness of the insoles. The ANOVA results for the surface roughness of the insoles are summarized in Table 6 (a) and (b). The P-value and its % contribution were occupied into concern to the significance level of all variables. In the present study, the second regression model provided the P-value less than 0.05 indicating that both models have a significant effect on the response. Moreover, the values of the contribution (%) for the response of surface roughness (the left and right foot insoles) are 78.62 % to 89.00 % respectively (with error 21.376 % and 11.00 %). Some of the model terms were found to be significant. For surface roughness of the left foot insole, E–F, C*C, CE, and DF are significant model terms, while the significant model terms of surface roughness of the right foot insole are C, A*A, and E*E.

Further, the percentages of contribution to the model linear, square and interactions between factors on the surface roughness of the left foot insole are 37.05% (linear), 15.24% (square) as well as 15.13% (interactions between factors). Factor E and F contribute more significant (17.20% and 17.04%), followed by factor C (1.73%), B (1.21%), D (0.95%), and A (0.42%) [Table 6(a)]. Similarly, for the surface roughness of the right foot insole, factor C was the most effective factor with the contribution of 6.54%, followed by F (2.29%), D (1.27%), E (0.59%), B (0.30%) and A (0.22%) [Table 6(b)]. Correspondingly, the low value of surface roughness of shoe orthotic insole could be achieved by optimum milling conditions (feed rate and type of material EVA foam), which was in close agreement with the published works [23, 29, 30].

Table 6(a). ANOVA-surface roughness Ra of the left foot insole

Source variation	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	0.290	0.0033	2.19	0.163	3.59
B*F	1	0.264	0.2638	1.99	0.182	3.26
C*E	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(b). ANOVA-surface roughness Ra of the right foot insole

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 based modeling for surface roughness

The RSM was complemented for modeling and analyzing variables, which have affiliation between a dependent variable and independent variables. In this way, the trial results in CNC milling of EVA foam were applied to improve the mathematical models of Ra. Furthermore, the second-order model of surface roughness of Ra can be generated as a function of the machining parameters (toolpath strategy, spindle speed, feed rate and step over). Thus, the relationship between the surface roughness Ra and the milling parameters on this research can be expressed as follows [Equation (8)]:

$$\begin{aligned} R_a &= \beta_0 + \beta_1.A + \beta_2.B + \beta_3.C + \beta_4.D + \beta_5.E + \beta_6.F + \beta_7.A.B + \beta_8 A.C + \beta_9 A.D + \beta_{10} A.E \\ &+ \beta_{11} A.F + \beta_{12} B.C + \beta_{13} B.D + \beta_{14} B.E + \beta_{15} B.F + \beta_{16} C.D + \beta_{17}.C.E + \beta_{18} C.F + \beta_{19} D.E \\ &+ \beta_{20} D.F + \beta_{21} E.F + \beta_{22} A^2 + \beta_{23}.B^2 + \beta_{24} C^2 + \beta_{25} D^2 + \beta_{26} E^2 + \beta_{27} F^2 \end{aligned} \tag{8}$$

Accordingly, the mathematical model of the surface roughness (Ra) can be generated using the results of optimized milling parameters (A, B, C, D, E, F). Surface roughness (Ra) models can be expressed using the RSM as the following [Equations. (9) and (10)]:

$$\begin{aligned} Ra_{right\_foot} &= 77.9826 + 0.39A - 0.01875B + 0.133C + 134.941.D - 8.0156.E - 0.21735.F + \\ & 0.000011847.AB + 0.000679AC - 2.62278AD + 0.07579.AE - 0.3245.AF + \\ & 0.00000562BC - 0.00388BD + 0.0002168.BE + 0.0003677.BF - 0.10377.CD + \\ & 0.005315.CE - 0.005077.CF + 0.150138.DE + 13.582.DF - 0.1993.EF - \\ & 0.10051.A^2 + 0.000000489.B^2 - 0.0001147.C^2 + 13.3907.D^2 + 0.06875.E^2 - 1.4355.F^2 \end{aligned} \tag{9}$$

$$\begin{aligned} Ra_{left\_foot} &= -104.433 - 0.155A + 0.00577B + 0.1403C + 168.1225D + 0.7259E + 1.104F \\ & + 0.00007094AB - 0.000932AC + 1.6817AD + 0.2AE + 0.0754AF - 0.000001164BC \\ & - 0.004453BD - 0.0000678BE - 0.0002514BF - 0.07847CD - 0.000984CE - \\ & 0.012335CF - 1.2445DE - 8.6592DF + 0.27EF - 0.2548A^2 - 0.000000072B^2 \\ & - 0.00006307C^2 - 69.6138D^2 + 0.0504E^2 - 3.76036F^2 \end{aligned} \tag{10}$$

The models of Equations (9) and (10) were subsequently checked using a numerical method for determination of R^2. The response for surface roughness of the right and the left foot insoles developed in this study provides R^2 values of 97.80 % and 98.20 %, respectively. In this case, the R2 values are close to 100 %, which is desirable for this experiment. Therefore, the above models can be used to predict the surface roughness at the particular design parameters.

For better understanding, the interaction effect of machining variables on surface roughness, 3D-plots for the measured responses was developed using the equation (Equations. 9 and 10). The 3D surface graphs for the relationship between cutting parameters and the response of surface roughness are shown in Figure 5 (a), (b), (c), (d), and (e). In this case of the right foot insole, the minimum level of surface roughness could be achieved by milling of EVA foam with the lowest hardness, the middle position of spindle speed and high level of toolpath strategy and step over. However, the minimum surface roughness of the left foot insole resulted in feed rate and spindle speed, toolpath strategy and step over at low levels, while EVA foam at any level of hardness. The explaination of the result that the feed rate increasing for machining process with yields vibration and more generate heat and hence contributing to the higher value of surface roughness according by [31]. It seems that the lowest step over resulted in a reduction in the value of surface roughness. Moreover, a complicated relationship between wide tolerance, the hardness of material and surface roughness of both insoles is shown in Figure 5(e.) The lowest wide tolerance of insoles resulted in the minimum surface roughness.

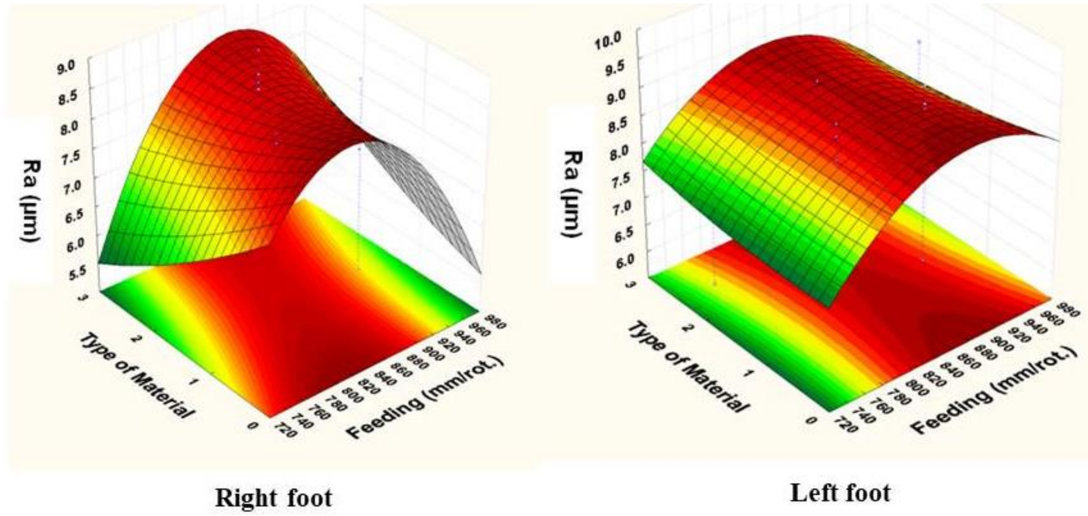


Figure 5. (a) Plot 3D curve of Ra vs Type of Material Eva Rubber foam – Feeding (mm/min).

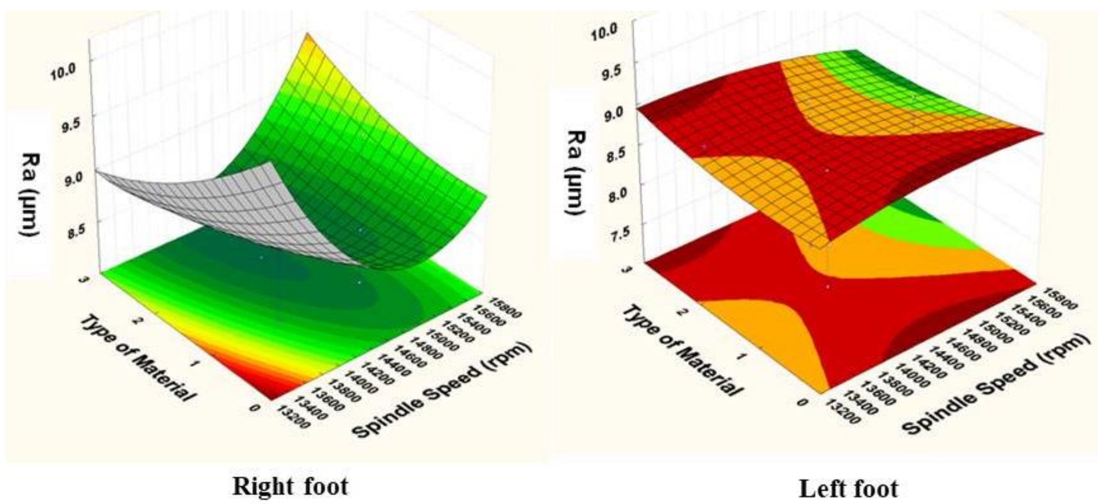


Figure 5. (b) Plot 3D curve of Ra vs Type of Material Eva Rubber foam – Spindle Speed (rpm)

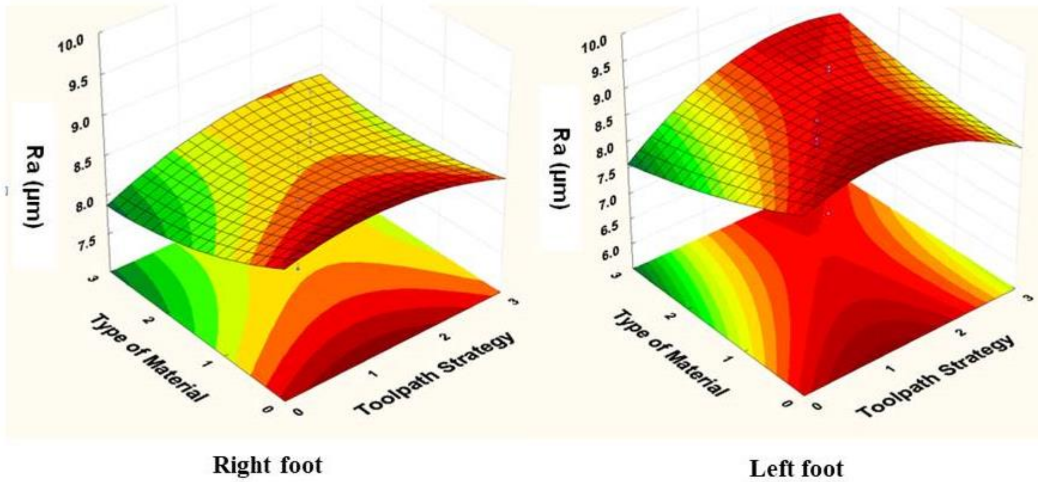


Figure 5. (c) Plot 3D curve of Ra vs Type of Material Eva Rubber foam – Toolpath Strategy

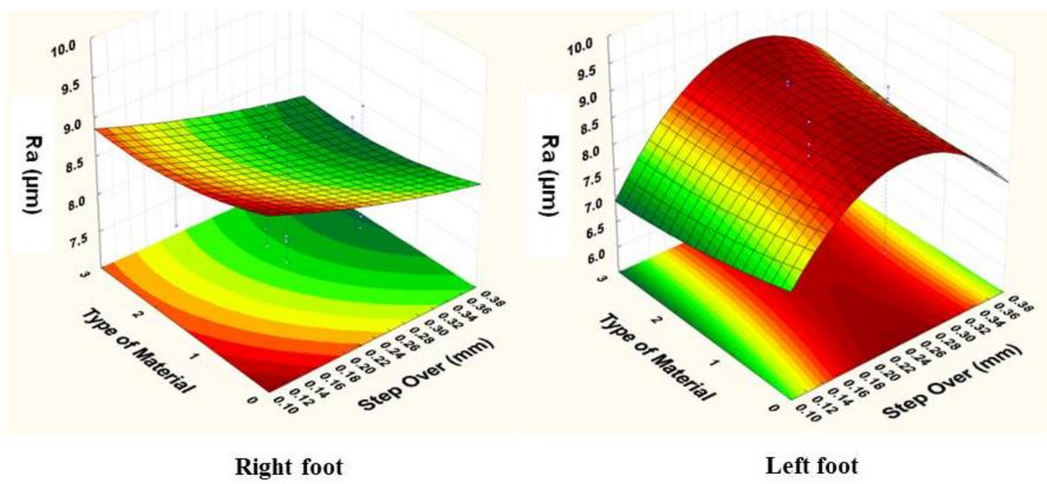
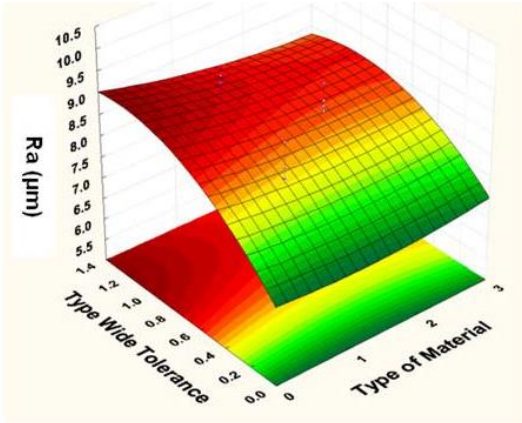
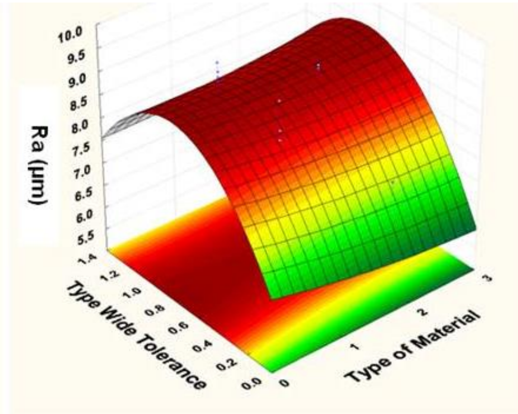


Figure 5. (d) Plot 3D curve of Ra vs Type of Material Eva Rubber foam – Step over (mm).





Right foot Left foot

Figure 5. (e) Plot 3D curve of Ra vs Type Wide Tolerance – Type of Material.

The prediction capability of the developed model was performed by a separate setup for experimentation, providing that value of Ra for the right and the left foot insoles is 8.538 µm and 7.828 µm, respectively. The predicted values matching to the control parameters are toolpath strategy of raster 450, spindle speed of 14,500 rpm, the feeding rate of 850 mm/min, step over about 0.25 mm, the best EVA foam with hardness 20-35 HRC (Level 1) with the typical design of insoles with wider tolerances of 0.75 mm. In this condition, the predicted values lead to similar trend as experimental values in CNC milling machine with absolute average percentage errors for both insoles is less than 3.6 % (Table 7). The results indicate that the proposed model performs satisfactorily [23, 26, 30].

Correspondingly, EVA foam with hardness ranged 20-35 HRC is the most appropriate for an insole shoe orthotics. This material is often used as a semi-rigid insoles [32]. In the present study, CNC milling of EVA foam with varying hardness performed satisfactorily to provide surface roughness at the range of 7-9 µm. The chip formed during machining was the granules or soft pieces-liked shapes, which can be wasted completing on the flute ball nose cutter milling. In terms of economic value, the use of EVA foam with the size of 1200 x 2400 x 30 mm (price $31/sheet) for insole provides the lowest cost product. Hence the EVA foam with low hardness and low cost may be the best level and the best typical design of insoles with wider tolerance.

Table 7. The optimum parameters and the confirmation results of the experimental and predicted values by the Response Surface method.

Cutting Parameter Conditions Optimal	Toolpath	Spindle Speed	Feed Rate	Step over	Type of Material Eva rubber Foam	Width Tolerance	Roughness Surface (Ra_Based on)		Percentage Error (%)
		(RPM)	(mm/min)	mm	(HRc)	(mm)	Exp.	RSM	
							µm		
$A_2B_2C_2D_2E_1F_2$	RASTER 45	14,500	850	0.25	20-35 HRc	0.75	**8.432**	8.538	1.26
$A_2B_2C_2D_2E_1F_2$	RASTER 45	14,500	850	0.25	20-35 HRc	0.75	**7.557**	7.828	**3.59**

Tabel 8. Comparison of the optimum and predicted results.

Optimization technique	Ra				Absolut % error	
	Optimal		Predicted			
	Left Foot (µm)	Right Foot (µm)	Left Foot (µm)	Right Foot (µm)	Left Foot	Right Foot
Taguchi approach (TM)	7.554	7.332	6.936	6.752	8.18	7.91
TM-RSM approach	7.572	7.648	8.538	7.828	11.31	2.30
Percentage (%) improvement	0.24	4.13	-	-		

Optimization Using Desirability Function Analysis with TM-RSM

In this method, the parameters analyzed of predicted response can be converted into a desirability value (dF) [33]. The ranges scale of dF is between 0 and 1. If the value of dF = 0 or closes in 0, then the response is considered completely unacceptable. If dF equals to 1 or closes in 1, then the response value is perfect for the target value. In this study, the desirability function was selected as "the smaller the better" because the minimum surface roughness was achieved at the optimum process parameters. The composite desirability (D) and the optimum response corresponding to each control parameter obtained has been analyzed by MINITAB and shown in the Figure 6.

The predicted optimum value of Ra (the left foot insole) is 7.572 µm at factor A (level 3), factor B (level 3), factor C (level 1), factor D (level 3), factor E (level 1) and factor F (level 2). In contrast, the predicted optimum value of Ra (the right foot insole) is 7.648 µm at factor A (level 2), factor B (level 2), factor C (level 2), factor D (level 3), factor E (level 3) and factor F (level 1). Moreover, the desirability values for the left and right foot insoles are 0.98766 and 0.94375 respectively, and hence the desirability value of Ra is close to 1.0. Consequently, the response is considered perfect for the target value.

A confirmation research has been directed to predict the optimum condition and result (experiment) Ra = 8.432 µm and 7.557 µm (for the left and right foot insoles) (Table 7). The prediction ability of the established model has been verified in the optimal condition. The Ra predicted = 8.538 μm and 7.828 μm has been got by established the model. The optimal outcomes gained by different optimization methods (TM and TM-RSM) are associated and got the significant enhancement in surface product with the hybrid method. The expected and relative analysis at optimal result has been summarized in Table 8. It has been observed (Table 8) that hybrid optimization technique of TM-RSM provides 0.24% and 4.13% same surface quality as associated to the optimal outcome that gained from Taguchi method. It has also been result that prediction ability of developed model is significant at 11.31% and 2.30% error for both insoles at the optimal condition gained by the hybrid method.

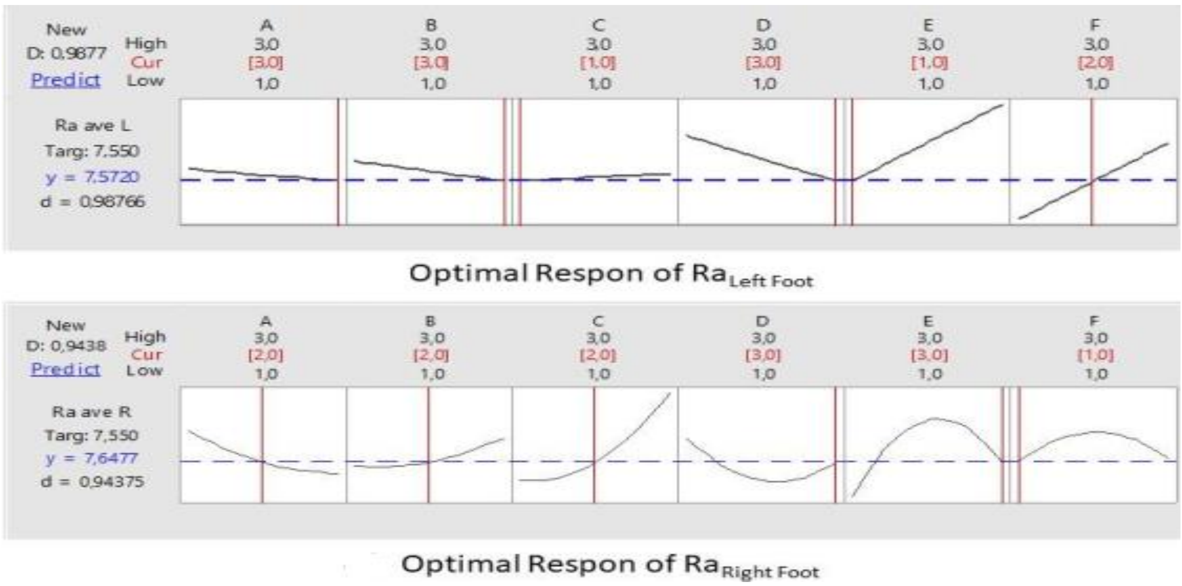


Figure 6. Optimized result of TM-RSM approach
(D=composite desirability; d= individual desirability; High = highest value parameter; Cur = optimal current value of control parameter; Low = lowest value parameter, y = response parameter, Ra = average surface roughness; A = toolpath strategy; B= spindle speed; C= feed rate; D = step over; E = EVA foams with variable hardness; F = typical design of insoles with wider tolerance).

In the present research, the hybrid methods of TM-RSM has been successfully applied for modeling and optimization in CNC milling of EVA foam for orthotic shoe insoles. It should be noted that based on the best author's knowledge, this work is the first study on exploring and combining the experimental and modelling approaches for manufacturing a rubber based product in CNC milling. Most of the previously published works [23, 26, 30, 31, 34] pointed out the investigation of process parameter in turning process. In addition, with respect to the CNC milling researches, the workers [28, 29, 33, 35] only focused on the determination of optimal parameters applied on flat surface.

CONCLUSION

In the present research, the hybrid method of TM-RSM has been applied for modeling and optimization in CNC milling of EVA foam for orthotic shoe insoles. Following conclusions have been got from modelling and optimization:

1. The 3D surface roughness plots illustrates the interactive effect of hardness of EVA foam and the feeding rate, step over, spindle speed and tool path on the yields of surface roughness. The Ra value decreases with an increase in the hardness value of EVA foam, step over and spindle speed, while the best Ra value was observed at a low level of hardness of EVA foam.
2. The optimum cutting conditions obtained by the TM approach show the value of the optimum Ra = 6.936 μm (the left foot insole) and 6.752 μm (the right foot insole). The optimal combination of the $A_2B_3C_1D_2E_1F_2$ and $A_2B_2C_2D_2E_1F_2$ is as a tool path strategy = raster 450, spindle speed =14500 – 15000 rpm, feed rate = 800-850 mm/min, step over = 0.25 mm, hardness of EVA foam = 20-35 HRC, and the type of wide tolerance = 0.75 mm.
3. The optimum cutting condition based on RSM approach provides the value of the optimum Ra = 7.828 μm (the left foot insole) and Ra = 8.538 μm (the right foot insole). Both are in the optimal condition of $A_2B_2C_2D_2E_1F_2$ with optimum control parameters as a tool path strategy = raster 450, spindle speed = 14500 rpm, feed rate= 850 mm/min, step over = 0.25 mm, hardness of EVA foam = 20-35 HRC, and the type of wide tolerance = 0.75 mm.
4. The optimal combination gained by TM-RSM based hybrid method are the raster toolpath strategy of 450 and step & shallow machining, spindle speed of between 14500 – 15000 rpm, feed rate of 800 mm/min and 900mm/min, step over about 0.3 mm, hardness of EVA foam of 20-35 HRC, and 50-60 HRC and the type of wide tolerance of 0.50-0.75 mm. The optimum value of prediction provides the optimum Ra = 7.572 μm and 7.648 μm for the left foot and right foot insoles, respectively.
5. The surface texture gained by the hybrid method is better (0.244% for the left foot and 4.13% for the right foot insoles) as compared to the optimum value of the Taguchi method.
6. Eva rubber foam with the hardness of 20-35 HRC is suggested to be most optimal material insoles which can be manufactured in the CNC milling.
7. Both methods (TM approach and TM-RSM approach) may be beneficial for optimization of input data in milling operations of orthotic shoe insoles leading to reduce the manufacturing time and cost.

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