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Investigation of Optimal Proses Parameters in CNC Milling of Insole Shoe Orthotic using Taguchi - Fuzzy Approach

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Abstract

The surface quality and processing time for insole shoe orthotic (*iso*) made from EVA rubber foam (*erf*) is highly dependent on the input machining strategies during a CNC milling process. This paper aims to clarify the application of Fuzzy Logic integrated with the Taguchi method to minimize the surface roughness and maximize Material Removal Rate (MaRR) that for *iso* product with *erf* based on CNC Rolland Modella machines. In this research, the input parameters specified are feed, DOC, and the composition of *erf*. In Taguchi method, orthogonal array design $L_8 2^4$ which consists of three factors and mix level and S/N will be calculated. S/N ratio of roughness and MaRR will be entered into the system of fuzzy logic and output received is multi response performance index (MRPI) with application ANOVA, DOC and feeds. Based on the result, it can be concluded that the optimal level for Erf is level 2 (*3rd Slice)*, feed is level 2 (2000 mm/min) and DOC is level 1 (2.5 mm) with the Ra=9.679 µm and MaRR=61,200,000 mm^3/min.

Keyword: EVA rubber foam (erf), fuzzy logic, Material Removal Rate (MaRR), orthotic insole shoe, surface roughness

INTRODUCTION

Custom insoles are frequently prescribed for individuals with diabetic neuropathy to offload high pressures from the metatarsal heads and other areas, which reduces the risk of plantar ulceration. Insoles provide the important interface between the foot and the shoe and, together with outsole modifications offer the most direct approach to the reduction of potentially damaging tissue stresses on the plantar aspect of the foot. Ethylene vinyl acetate (EVA) rubber foam material is popular used in the shoe and insole shoe field [1] mainly because it demonstrates excellent mechanical properties including light weight, shock resistance, and high elasticity. To procedure the insole shoe product shape accurately by using the EVA rubber foam material, the manufacturing procedure with CNC machine is the crucial step.

Orthotics are all equipment that are added to the human body to stabilize the body, prevent disability, to protect from injured, or assist the function of the limb. Orthotic shoe insole is a device that designed to restore the function of malformed foot. Especially for Diabetes Mellitus (DM) patience. DM is one of the most common and rapidly increasing health problems worldwide. The number of people in the developing world with diabetes will increase by more than 2.5-fold, from 84 million in 1995 to 228 million in 2025 [2]. Indonesia's DM patience almost reaches 10 million people in 2015. With the rise in prevalence of DM, the burden of this disease to society becomes progressively greater [2]. Pathologies of the foot due to DM are a significant contributor to the economic burden [3]. An estimated 25 percent of DM patients experienced foot problems [4], and about 20 percent of diabetic patients entering the hospital are admitted because of foot problems [5]. Studies showed that complications of DM, such as changes in bony structures, limited joint mobility, callus formation, and arterial in sufficiency may cause locally elevated plantar pressures [6–8]. Repeated applications of such high pressures make the foot more susceptible to the development of ulcers [9].

In routine clinical practice, DM patients are often given a special insole for ulcer prevention. Especially for those neuropathic patients who lose sensation in their feet, a proper insole support should help maximize the contact area and reduce locally high plantar pressure and pressure time integral (PTI) when walking. If the prescribed insole is not properly shaped and the foot structure cannot be balanced, the foot plantar soft tissues will become overstressed and may develop ulcers with accumulative trauma disorders [10]. A better cast can be made from other loading conditions for custom-molded insoles. A lack of objective in formation exists in choosing an insole-casting condition for the needs of particular subject groups. Knowledge of the pressure redistribution with different insole shapes can offer guidance for the better design and construction of a comfortable and functional support.

The Taguchi design of experiment is a powerful method used to achieve high quality in lesser no of experiments. It provides better setting as compared to traditional experimental designs which are time consuming due to a large number of experiments and most of the time not feasible [1]. The Taguchi methods reduces the sensitivity of quality characteristics to various unknown noise factor. Large number of papers have been published on Taguchi technique handling single output response. However, working with multiple responses is still an interesting area of research problem. Fuzzy logic deals with uncertain and vague data. Fuzzy logic system converts the multiple performance characteristic into single multi response performance index (MRPI) [6]. Hence the optimization of multiple performance characteristic is well handle by integrated Taguchi-Fuzzy logic, which was optimization of multiple performance characteristics is well handled by integrated Taguchi-Fuzzy logic, which was not possible by the Taguchi method alone [4]

Following this main frame, in the present study based on Taguchi – fuzzy approach, the functions of different insoles cast under different loading conditions in redistributing the interfacial pressures during walking are compared. In addition, the correlation between the parameters of the surface roughness machining strategy and working time products *iso* that made from EVA foam rubber is investigated in more deep way.

METHOD

In this paper Rolland Modella MDX – 40R was used for experiment. The 6 mm diameter end milling cutter of SECO (93060F) was used for machining. The machining parameters was selected on the basis of various trial runs by checking their effect on surface roughness. Initially, the parameters considered for experiment, L_8 orthogonal array was used. This L_8 orthogonal array was prepared for parameter combination of composition Eva Rubber, feed, and depth of cut. Roughness surface is selected as the response to measure and determine whether the three parameters actually affect significantly the machining process insole shoe orthotic. The differences in the number of layers of material Eva Rubber set as a factor in this study to see whether it will give effect on the magnitudes of the resulting surface roughness.

It should be noted that Taguchi recommends the use of a three-stage process to achieve the desirable product quality by design, three stages being system design, parameter design and tolerance design [9]. In this paper, Taguchi approach was used and integrated with fuzzy logic to handle multiple responses such as surface roughness and material removal rate. The S/N ratios of responses are taken as the input to the fuzzy logic system and converted to multi response performance index (MRPI) which gives an idea about simultaneous performance of multiple responses. Figure 1 shows some steps to create insole shoe orthotic in the experiment

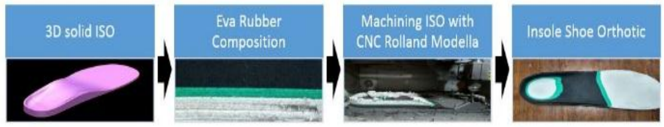

Figure 1: Process stages Experiment

Experimental methods are too complex and require a large number of experience as number of process parameter increases. The Taguchi method uses a special design called orthogonal array to study the entire space of parameters with lesser number of experiments. The experimental results are converted into signal to noise ratios (S/N). The signal to noise ratio gives an idea about performance characteristic deviating from desire value. The large the S/N ratio lesser is the deviation of performance characteristic from desired value. [8]

There are three type of performance characteristics in analysis of S/N ratio: The lower-the-better, the higher-the-better and the nominal-the-better. Irrespective of the type of performance characteristic, the optimal level of process parameter is with the higher S/N ratio. The Taguchi method is a design to handle single performance characteristic. Hence the optimization of multiple performance characteristic is still an area research. In this paper, Taguchi method is integrated with fuzzy logic to handle multiple responses that are surface roughness and material removal rate. The S/N ratios of responses are taken as taken as the input to the fuzzy logic system and converted to multi response performance index (MRPI) which gives an idea about simultaneous performance of multiple responses. Large the MRPI better is the performance of multiple responses.

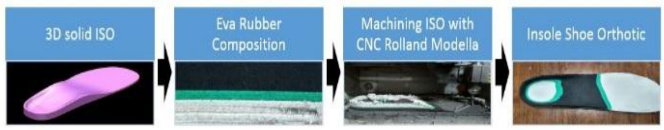

Figure 2: Process Stages Experiment

RESULTS AND DISCUSSIONS

Machining performance evaluation

To get the accurate response data of surface roughness and material remove rate, then the precision measuring instruments is required. The surface roughness tester, the Hommel-Etamic T1000 series is used to measure Ra/C.L.A values of surface roughness. MaRR can be obtained by calculating the equation 3.

$$\text{MaRR} = n\, N\, f\, a_p\, a_e \ldots\ldots \quad (1)$$

where n is spindel speed (rpm), N is the number of tooth, and a_p the depth of cut. For detail, machining parameters and levels used in the present study is shown in Table 1.

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Table 1: Machining parameters and levels

Factor	Level			
	1	2	3	4
Composition of Eva Rubber	2nd *Slice*	3rd *Slice*	4th *Slice*	5th *Slice*
Feed (mm/min)	1500	2000	3000	3500
DoC (mm)	2.5	3.5	4.0	5.0

Erf with dimensions 250 x 95 x 21 mm is used in this experiment. The value of material hardness ranges from 40-60 HR_C. This material can be used in healthcare solutions such as: orthopedic shoes, insoles, exercise mats, orthotic support [4]. The physical and mechanical properties of these materials include density of 55-65 kg/m^3, nominal sheet size (trimmed) of 2000 x 1000 mm, nominal thickness (split) of 3-36 mm, tensile strength of 800 kPa, and tear strength of 4.5 kN/m. In addition, the hardness after 2 second reads 25-30 degrees. While, the chemical composition of *Erf* can be found in Table 2.

Table 2: The chemical composition of rubber EVA Foam [11]

Material	Properties	Value	Source
Ethylene Vinyl acetate (EVA)	Melt flow index (g/10 min)	2.00	PIL Madras
	Density (g/cm^3)	0.937	
	Vicat softening point (ºC)	59	
	Vinyl acetate (wt%)	18	
	Viscosity (g/cm^3)	0.170	

Optimization of machining parameter

This section explains the concept of integration Taguchi - Fuzzy logic used to get the parameters of orthotic shoe insole machining processes on CNC machines Rolland Modella - 40R, so that the surface roughness and the optimal MaRR will be obtained.

In this work, orthogonal array that constructed is based on 3 factors (Composition *Erf*, feed, and DoC). As a note, one factor is the composition of *Erf* which is set at four levels (*2nd Slice, 3rd Slice, 4th Slice, 5th Slice*). However, the speed factor and finishing raster toolpath strategies were excluded in this experiment because the optimal rpm on the previous experiment is15000 rpm [10]. Factors of feed and DoC are set to two levels. Combination treatment in this experiment can be shown in the Table 3 and 4 below.

Table 3: Experimental layout and responses L_8 4 x 2^2

No	Eva Rubber	Feed (mm/min)	DoC (mm)	Ra_1 (µm)	Ra_2 (µm)	Ra_3 ((µm)	$Ra_{average}$ (µm)
1	1	1	1	10.00	10.21	10.71	10.307
2	1	2	2	10.67	9.858	10.70	10.409
3	2	1	1	9.478	10.05	10.49	10.006
4	2	2	2	10.29	9.192	9.323	9.602
5	3	1	2	8.872	10.54	9.317	9.576
6	3	2	1	9.747	9.832	9.457	9.679
7	4	1	2	10.11	9.812	9.338	9.753
8	4	2	1	9.481	9.705	10,75	9.979

Table 4: S/N Ratio L_8 4 x 2^2

No	Eva Rubber	Feed (mm/min)	DOC (mm)	Ra average (µm)	S/N ratio	Membership Function	MaRR (mm^3/min)
1	1	1	1	10.31	0.08869	0.2367	54,000,000
2	1	2	2	10.41	0.15213	0.2807	102,000,000
3	2	1	1	10.00	0.17166	0.3373	54,000,000
4	2	2	2	9.60	0.23976	0.3660	102,000,000
5	3	1	2	9.58	0.49733	0.5560	90,000,000
6	3	2	1	9.68	0.02577	0.1250	61,200,000
7	4	1	2	9.75	0.10105	0.2573	90,000,000
8	4	2	1	9.98	0.30584	0.4230	61,200,000

Based on Table 4, the optimal level for *Erf* is level 3 (*4th Slice)* while for feed the optimal level is level 2 (2000 mm/min) and DOC is level 1 (2.5 mm) with the R_a = 9.679 µm and MaRR = 61,200,000 mm^3/min.

Setting level selection for significant factors

For the selection of the setting levels for each factor, selected value for level corresponding to the data common practice in the field is shown in Table 5. It can be seen that the value of the data processing at each level is selected. The value chosen is based on practical experience that has often performed during the machining process.

Table 5: Setting level selection (1) based on R_A

No	Eva Rubber	Feed (mm/min)	DOC (mm)	Ra_1 average (µm)	Membership Function	MaRR (mm^3/min)
1	1	1	1	10.307	0.2367	54,000,000
2	1	2	2	10.409	0.2807	102,000,000
3	2	1	1	10.006	0.3373	54,000,000
4	2	2	2	9.602	0.3660	102,000,000
5	3	1	2	9.576	0.5560	90,000,000
6	3	2	1	9.679	0.1250	61,200,000
7	4	1	2	9.753	0.2573	90,000,000
8	4	2	1	9.979	0.4230	61,200,000

Based on Table 5, it can be found that the optimal level is level 3 (*3rd Slice)* for Erf, =level 2 (2000 mm/min) for feed and level 1 for DoC (2.5 mm) with the *Ra* = 9.679 µm and MaRR = 61,200,000 mm^3/min. The cutter feed used is at level 2 (i.e. 2000 mm/min for finer quality). Number of erf slice is = 4, DoC of product quality = 2.5 mm.

As a note, setting of cutter type is influenced by the type of material and the size of the cutter. Selected level 2 for the use of cutter type 1 (Endmill MEH) to produce chips will stick to the cutter. In this way, the quality of the product is less than smooth surface. The use of cutter type 2 (Endmill SECO) to produce chips will be removed directly from the cutter to create more refined product surface quality. Based on the results, it can be found that the factors significantly affect the machining process from highest to lowest grade is factor C by 52.82%, factor D by 33.11% and factor B by 7.02%.

CONCLUSIONS

This study demonstrates the application of Fuzzy Logic integrated with the Taguchi method to minimize the surface roughness and maximize Material Removal Rate (MaRR) for enhancing the surface quality and processing time for EVA rubber foam (*erf*) insole shoe orthotic. Based on the discussion above, the conclusion can be drawn as follows:

1. The optimal level for Erf is level 2 (*3rd Slice)*, feed is level 2 (2000 mm/min) and DOC is level 1 (2.5 mm) with the Ra=9.679 µm and MaRR=61,200,000 mm^3/min.
2. The depth of cut (26.432%) and type cutter (15.877%) have a major influence on surface roughness of insole shoe orthotic. The interaction of several parameters considered here has a significant effect on the surface roughness.

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