Surface Lapping Process Improvement via Steepest Ascent Method Based on Factorial and Simplex Designs

Sitthikorn Duangkaew* and Pongchanun Luangpaiboon, *Member, IAENG*

***Abstract*—This research focuses on the lapping process optimization by designed experiments and response surface methods. The lapping process intends to introduce a finely ground flat on disk clamp, the lapping process will remove material from the disk contact radius and provide the desired dimension of the surface. The lapping plate is produced by cubic boron nitride materials. Its mechanism and characteristics are very complicated to conduct and investigate. In addition, the two-level factorial design was applied to a preliminary study, the analysis of variance was performed to determine the optimal combination of process variables which consist of lapping time, lapping speed, downward pressure and charging pressure. The desirability function approach of the nominal-the-best was used to compromise the multiple responses of material removal, lap width and clamp force into single response called the overall desirability (D). Firstly, the multiple regression models were developed from the statistically significant parameters. Secondly, the multi regression model in forms of the path of steepest ascent moved the region of experimental region toward the design point with the maximal D level. After the path of steepest ascent deteriorated the modified simplex method was integrated to drive the process achieving the optimal condition. The experimental results showed that there is a significant D increase to the level of 0.92, approximately 50% when compared to the current operating condition. The optimal condition of process variables which consist of lapping time, lapping speed, downward pressure and charging pressure are 49 sec., 26 rpm, 6.9 psi and 7.7 psi, respectively.**

***Index Terms*—Desirability Function Approach, Modified Simplex Method, Steepest Ascent Method, Surface Lapping Process.**

I. Introduction

LAPPING process is the process which a material is precisely removed from a work piece (or specimen) to produce a desired dimension, surface finish or shape. A process of lapping has been applied to a wide range of materials and applications, ranging from metals, glass, optics, semiconductors and ceramics. Typical examples are finishing of various components used in the aerospace, automotive, hard disks and its components, mechanical seal, fluid handling, and many other precision engineering industries. Lapping processes are used to produce dimensionally accurate specimens to high tolerances (generally less than 2.5 μm uniformity). The lapping plate will rotate at the low speed, less than 80 rpm, and the mid-range abrasive particle of 5-20 μm is typically used [1].

The material removal of work pieces is the main requirement of lapping to meet the process specification including a surface lap width and a desired clamp force. In order to maintain the reliability and lifetime of the produced work piece, it is essential to improve the machining process by optimizing both the lapping process efficient and the consideration of the process parameter influences with surface lap width and clamp force according to customer specifications. The initial of material removal, surface lap width and clamp force have somewhat different values on the mean and standard deviation (Stdev), ranging from 1.384 mm^3 for material removal, 0.76 mm for surface lap width and 26.59 kgf for the clamp force as shown in Table I.

TABLE I
Quality Characteristics on The Current Operating Condition

Response variable	Mean	Stdev	Process requirement
Material removal	1.384	0.134	1.0 ± 0.75 mm^3
Response variable	**Mean**	**Stdev**	**Customer requirement**
Surface lap width	0.765	0.027	0.65 ± 0.20 mm
Clamp force	26.59	0.432	28.0 ± 3.0 kgf

II. Surface Lapping Process

A. Process Review

Single side lapping is the most frequently used machining process for producing the desired dimension.The advantages of this type of lapping are that many pieces can be machined at one time and beside this, the work holding is very simple, cut rates are consistent and close accuracies are inherent with the process. The machines used in this lapping have a rotating annular-sharped lap plate and work pieces are placed on the flat rotating wheel as shown in Fig. 1. Lapping mainly includes a lap plate, lapping fluid and conditioning ring [2]. Lap plates are made of cubic boron nitride (CBN) with the size of 20 μm, hexagonal tiles of 92% minimal coverage. Lapping fluid is with the cutting fluid Alpha-2, conditioning plate with Al_2O_3 grit size#220.

The lapping process consists of four operation steps as shown in Fig. 2. After the part loading into carrier then place a white plastic for retaining ring around parts and template including a neoprene. A suction cup is performed to place a flat aluminum plate on a top of neoprene. The next step is to slide the white plastic retaining ring onto the

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lapping plate then actuate the pressure plate down. The main process is to lap a part with the coolant on and simultaneously apply the pressure on a disk, charge Al_2O_3 pressure, speed up the lapping plate and lapping time. The final steps are to unload the part, clean and dry [3-4].

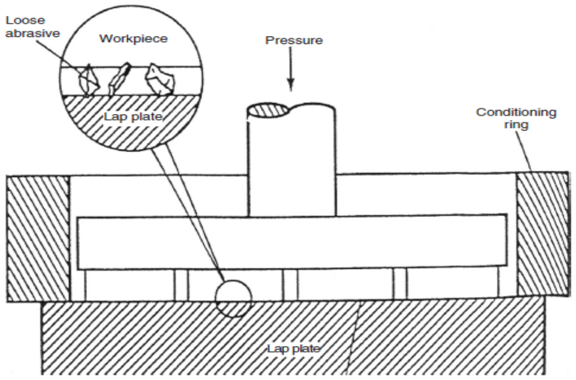

Fig. 1. Schematic Single Side Lapping Process [2]

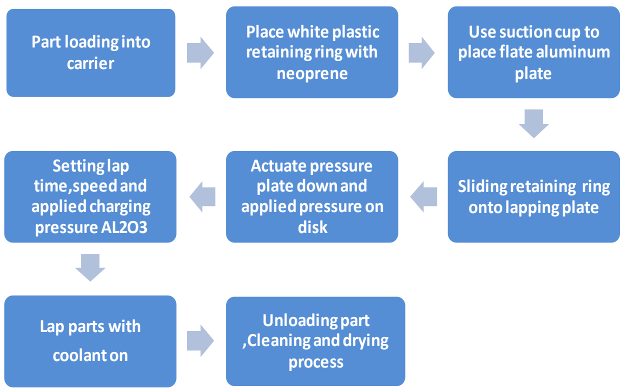

Fig. 2. Surface Lapping Process

B. *Lapping Process Variables*

After brainstorming via teams who work for the lapping process e.g. advance process development engineer, process engineer, product engineer and quality engineer, the key controllable process variables influencing the lapping characteristics include (1) lapping time (2) lapping speed (3) downward pressure and (4) charging Al_2O_3 pressure (Table II).

TABLE II
THE FOUR PROCESS VARIABLES AND THEIR TYPE

Symbol	Process variable	Type
X_1	Lapping time	Quantitative
X_2	Lapping speed	Quantitative
X_3	Downward pressure	Quantitative
X_4	Charging pressure	Quantitative

C. *Lapping Process's Quality Measurements*

The responses of interest are the material removal (MR), lap width and clamp force. The material removal (MR) is compared with the process requirement specification, the lap width and clamp force are measured and compared with customer requirement specifications. The process and customer specification are required to meet their targets.

III. Lapping Process Optimization Method

Response surface methodology (RSM) is one of the modeling and optimization approaches currently in wide spread applications in describing the performance of the manufacturing process and finding the optimum of a response of interest. RSM is a collection of mathematical and statistical techniques that are benefit for modeling and analyzing problems in which a response of interest are affected by some process variables and the objective is to optimize the response [5-6]. If all process variables are assumed to be measurable, the response surface can be determined by the regression analyses. In product or process improvement, however, it is quite simple that there are many responses of interest. In this case, determination of optimal operating conditions on the process variables would require simultaneous consideration of all the responses or a multiple response problem. There are three stages for solving the multiple response problems which consist of data collection, model building, and optimization.

A. *Desirability Function*

The desirability function approach transforms an estimated response (e.g., the *i*th estimated response of $\hat{y}_i$) into a scale-free value, called a desirability (denoted as $d_i(\hat{y}_i(x))$ for $\hat{y}_i$). The values are between 0 and 1, and increase as the corresponding response values becomes more desirable. The overall desirability *D*, another value between 0 and 1, is defined by combining the individual desirability values (i.e., $d_i(\hat{y}_i(x))$'s) [7]. Then, the optimal setting is determined by maximizing D. In this research, the desirability function for a nominal-the-best (NTB) type response is defined as

$$d_i(\hat{y}_i(x)) = \begin{cases} 0 & \text{if } \hat{y}_i(x) < Y_i^{min} \text{ or } y_i(x) > Y_i^{max}, \\ \left[\dfrac{\hat{y}_i(x) - Y_i^{min}}{T_i^{min} - Y_i^{min}}\right]^{si} & \text{if } Y_i^{min} < \hat{y}_i(x) < T_i^{min}, \\ \left[\dfrac{Y_i^{max} - \hat{y}_i(x)}{Y_i^{max} - T_i^{max}}\right]^{ti} & \text{if } T_i^{max} < \hat{y}_i(x) < Y_i^{max}, \\ 1 & \text{if } T_i^{min} < \hat{y}_i(x) < T_i^{max}, \end{cases}$$

; where $d_i(\hat{y}_i(x))$ is the desirability function of $\hat{y}_i(x)$, Y_i^{min} and Y_i^{max} are respectively, the lower and upper bounds on the response. T_i^{min} and T_i^{max} ($T_i^{min} \leq T_i^{max}$) are, respectively, the lower and upper targets of the response. s_i and t_i are the parameters that determine the shape of $d_i(\hat{y}_i(x))$: if s_i (or t_i) = 1, the shape is linear; if s_i (or t_i) >1,convex; and if 0 < s_i (or t_i) < 1, concave. It should be noted that, if T_i^{min} = T_i^{max}, the trapezoidal desirability function reduces to a triangular one.

In this research, defined s_i and t_i equal to 1, the shape is linear, and y_1 is the response of material removal (MR). The Y_i^{min} = 0.25 and Y_i^{max}= 1.75 are respectively, T_i^{min} = 0.90 and T_i^{max} = 1.10 are respectively, $d_1(\hat{y}_1(x))$ is the desirability function of y_1 which is defined as

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$$d_1(\hat{y}_1(x)) = \begin{cases} 0 & \text{if } \hat{y}_1(x) < 0.25 \text{ } or \text{ } y_1(x) > 1.75, \\ \dfrac{\hat{y}_1(x) - 0.25}{0.90 - 0.25} & \text{if } 0.25 < \hat{y}_1(x) < 0.90, \\ \dfrac{1.75 - \hat{y}_1(x)}{1.75 - 1.10} & \text{if } 1.10 < \hat{y}_1(x) < 1.75, \\ 1 & \text{if } 0.90 < \hat{y}_1(x) < 1.10, \end{cases}$$

The actual response of y_2 is the response of lap width. $Y_i^{\min}$ and $Y_i^{\max}$ are 0.50 and 0.85, respectively. $T_i^{\min}$ and $T_i^{\max}$ are 0.625 and 0.675, respectively. $d_2(\hat{y}_2(x))$ is the desirability function of y_2 which is defined as

$$d_2(\hat{y}_2(x)) = \begin{cases} 0 & \text{if } \hat{y}_2(x) < 0.45 or \text{ } \hat{y}_2(x) > 0.85, \\ \dfrac{\hat{y}_2(x) - 0.45}{0.625 - 0.45} & \text{if } 0.45 < \hat{y}_2(x) < 0.625, \\ \dfrac{0.85 - \hat{y}_2(x)}{0.85 - 0.675} & \text{if } 0.675 < \hat{y}_2(x) < 0.85, \\ 1 & \text{if } 0.625 < \hat{y}_2(x) < 0.675, \end{cases}$$

The actual response of y_3 is the response of lap width. $Y_i^{\min}$ and $Y_i^{\max}$ are 25.0 and 28.0, respectively. $T_i^{\min}$ and $T_i^{\max}$ are 27.75 and 28.25, respectively. $d_3(\hat{y}_3(x))$ is the desirability function of y_3 which is defined as

$$d_3(\hat{y}_3(x)) = \begin{cases} 0 & \text{if } \hat{y}_3(x) < 25.0 \text{ } or \text{ } y_3(x) > 31.0, \\ \dfrac{\hat{y}_3(x) - 25.0}{27.75 - 25.0} & \text{if } 25.0 < \hat{y}_3(x) < 27.75, \\ \dfrac{31.0 - \hat{y}_3(x)}{31.0 - 27.75} & \text{if } 28.25 < \hat{y}_3(x) < 31.0, \\ 1 & \text{if } 27.75 < \hat{y}_3(x) < 28.25, \end{cases}$$

B. Steepest Ascent Method (SAM)

The procedure of steepest ascent is that a hyper plane is fitted to the results from the initial 2^K (fractional) factorial designs where K is the number of decision variables. The direction of steepest ascent on the hyper plane is then determined by using principles of least squares and experimental designs. The next run is carried out at a point which is some fixed distance in this direction and further runs are carried out by continuing in this direction until no further increase in yield is noted. When the response first decreases another 2^K design is carried out, centred on the preceding design point. A new direction of steepest ascent is estimated from this latest experiment. Provided at least one of the coefficients of the hyper plane is statistically significantly different from zero, the search continues in this direction. Moreover, the boundary limitations of the process variables are also determined as model constraints [8].

C. Modified Simplex Method (MSM)

A simplex is a K-dimensional polyhedron with K+1 vertices, where K is the number of decision variables for optimisation or the dimension of the search space. This sequential optimum search is based on moving away from the experiment with the worst result in a simplex consisting of K+1 experiments [9]. The objective of the sequential simplex method is to drive the simplex toward the region of the factor space which is of optimal response. The algorithmic details are as follows. The subsequent vertex is projected with a preset reflection coefficient to the centroid of the hyperface formed by the remaining simplex points a direction opposite from the worst vertex. The new symmetrical simplex consists of one new point and *m* design points from the previous simplex or discarding the worst point and replacing it with a new point. Repetition of simplex reflection and response measurement form the basis for the most elementary simplex algorithm. Many modifications to the original simplex algorithm have been developed. The details of sequential procedures for setting up the optimum value via a relationship of significant parameters and responses are depicted in Fig. 3.

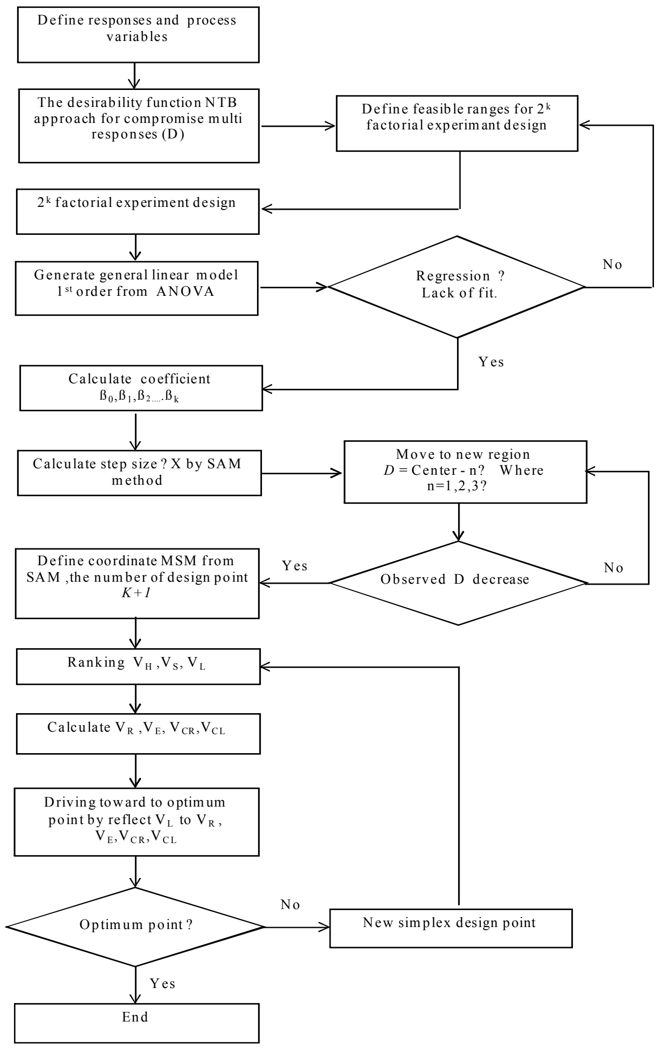

Fig. 3 Flow Chart of the Steepest Ascent Method Based on Factorial and Simplex Designs

IV. Experiment Result And Analysis

The process of lapping was characterized by individually computing the estimated effect in each process variables on the response via screening experiments. The experimental results and analyses to determine the statistically significant effects of four process variables of the lapping time (X_1), lapping speed (X_2), downward pressure (X_3) and charging pressure (X_4) are applied via the feasible ranges, the current operating condition and types of process variables as shown in Table III.

TABLE III
PROCESS VARIABLES, FEASIBLE RANGES AND CURRENT LEVELS

Process Variables	Feasible Ranges		Current	Unit
	Lower	Upper		
X_1	40	60	60	sec.
X_2	30	40	30	rpm
X_3	8.0	12.0	8.0	psi
X_4	8.0	12.0	8.0	psi

In this step, the objective of using a factorial experiment design is to analyze both main and interaction effects for all process variables. The 2^4 experimental designs with two replicates provide 32 treatments. The low and high levels were selected cover the values of feasible ranges from the actual operating condition. The material removal, lap width and clamp force were measured from an average value and an estimated responses were transformed into a scale free, denoted as $d_1(\hat{y}_1(x))$ for y_1 (material removal), $d_2(\hat{y}_2(x))$ for y_2 (lap width) and $d_3(\hat{y}_3(x))$ for y_3 (clamp force). It is the value between 0 and 1 and increases as the corresponding response value becomes more desirable.

The overall desirability D is defined by combining the individual desirability of $d_1(\hat{y}_1(x))$, $d_2(\hat{y}_2(x))$ and $d_3(\hat{y}_3(x))$ values then the optimal setting is determined by maximizing D. By using a general linear model from the analysis of variance (ANOVA), sources of variations focusing on the main and interaction effects and their P-value are shown Table IV. The statistically significant process variables via main effect analysis consist of X_1, X_2, X_3 and X_4 as P-value is less than or equal to 0.05 and the interaction effects of X_1*X_3 and X_2*X_3 are also statistically significant at the 95% confidence interval.

On the first scenario, the method of steepest ascent is then applied for statistically significant quantitative process variables of X_1, X_2, X_3 and X_4 to determine the most preferable fitted equation of associated process variables to the overall desirability D as shown in Table V. The relationship of the process variables and the compromise response of D in terms of the path of steepest ascent are as followed:

$$D = 0.592 - 0.172\, X_1 - 0.114\, X_2 - 0.0788\, X_3 - 0.0366\, X_4$$

TABLE IV
SOURCES OF VARIATION FOCUSING ON THE MAIN AND INTERACTION EFFECTS AND THEIR P-VALUE

Source of variance	P-value for D
X_1	0.000
X_2	0.000
X_3	0.000
X_4	0.025
$X_1 * X_2$	0.085
$X_1 * X_3$	0.004
$X_1 * X_4$	0.864
$X_2 * X_3$	0.011
$X_2 * X_4$	0.627
$X_3 * X_4$	0.306

TABLE V
REGRESSION MODEL INCLUDING ITS SIGNIFICANT COEFFICIENTS AND ANOVA TABLE

Predictor	Coef	SE Coef	T	P-value
Constant	0.592	0.01938	30.54	0.000
X_1	-0.17214	0.01938	-8.88	0.000
X_2	-0.11412	0.01938	-5.89	0.000
X_3	-0.07880	0.01938	-4.07	0.000
X_4	-0.03664	0.01938	-1.89	0.070

Source	DF	SS	MS	F	P-value
Regression	4	1.60663	0.40166	33.4	0.000
Residual Error	27	0.32466	0.01202		
Total	31	1.93129			

In order to move the center of 2^4 experiment design to get the maximal level of D, the proper coefficients are determined via the ratio of X_1: X_2: X_3: X_4 equalling 0.17214: 0.11412: 0.0788: 0.03664. It means that the 0.17214 units is moving in the direction of X_1, 0.11412 units in the direction of X_2 , 0.0788 units in the direction of X_3 and 0.03664 units in the direction of X_4 and all are in coded unit data. The coefficients for all process variables were measured by transforming into the natural unit to get 3.84 for X_1, 1.27 for X_2, 0.35 for X_3 and 0.16 for X_4. In this research the step size of 0.50 is selected. The results on the path of steepest ascent determine the near optimal values of process variables as shown in Table VI and Fig. 4.

TABLE VI
THE NEW LEVELS OF PROCESS VARIABLES ALONG WITH OVERALL DESIRABILITY OF D

Step size	Process variables				Desirability
	X_1	X_2	X_3	X_4	D
Center	60	30	8.0	8.0	0.455
Center-Δ	56	28	7.5	8.0	0.582
Center-2Δ	52	26	7.5	7.5	0.788
Center-3Δ	48	26	7.0	7.5	0.873
Center-4Δ	45	24	6.5	7.5	0.834
Center-5Δ	41	24	6.5	7.0	0.750

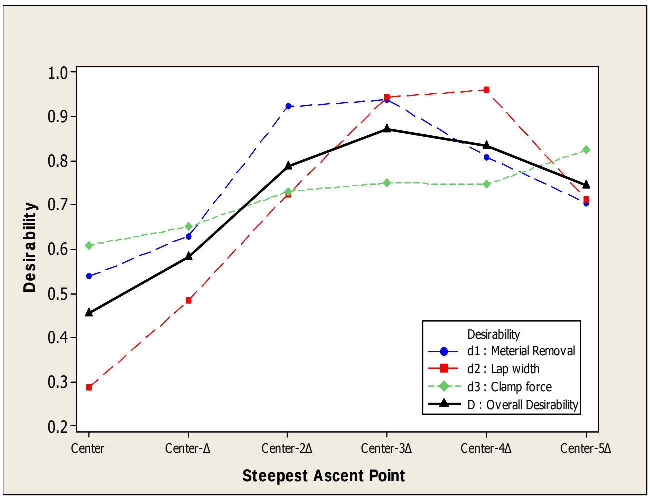

Fig. 4. Sequential Performance of the SAM Categorized by the Desirability Function Type

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From the Table VI, after the fourth step, the direction brings a decrease of the overall desirability D. It can be concluded that the direction of process variables to be changed in order to achieve an increase of the overall desirability is as followed: lapping time (X_1) of 48 sec., lapping speed (X_2) of 26 rpm, downward pressure (X_3) of 7.0 psi and charging pressure (X_4) of 7.5 psi.

On the second scenario, the modified simplex method is then applied to drive the region of process variables to an optimal response. Firstly, define the coordinate of the starting design point. The number of trials equal to K+1, where k is the number of process variables. In this study, K equals to 4 or the number of the total starting design points is 5 as shown in Table VII. All of these were selected from the steepest ascent path and ranked to V_H, V_{S3}, V_{S2}, V_{S1} and V_L. Secondly, the MSM is to drive toward to the optimum point by reflecting V_L to a new design point of V_R and observe its response.

$$V_R = \overline{P} + (\overline{P} - V_L)$$

, where $\overline{P}$ is the centroid of the remaining vertices except V_L. If the observed V_R is better than V_L but worse than V_S the V_{CR} and V_{CL} were selected to be the new simplex.

$$V_{CR} = \overline{P} + 0.5(\overline{P} - V_L)$$
$$V_{CL} = \overline{P} - 0.5(\overline{P} - V_L)$$

TABLE VII
THE INTEGRATION OF MSM AND SAM DESIGN POINTS

Vertex	X_1	X_2	X_3	X_4	D	Rank
1	48	26	7.0	7.5	0.87	V_H
2	45	25	6.5	7.5	0.83	V_{S3}
3	52	27	7.5	7.5	0.79	V_{S2}
4	41	24	6.5	7.0	0.75	V_{S1}
5	56	29	7.5	8.0	0.58	V_{L1}
$\overline{P}$	47	26	6.8	7.4		
V_{R1}	37	22	6.2	6.8	0.71	
V_E	27	19	5.6	6.1	-	
V_{CR1}	42	24	6.5	7.0	0.81	
V_{CL1}	51	27	7.2	7.7	0.84	

TABLE VIII
THE MASSIVE CONTRACTION OF PROCESS VARIABLES FROM THE MSM

Vertex	X_1	X_2	X_3	X_4	D	Rank
1	48	26	7.0	7.5	0.87	V_H
2	51	27	7.2	7.7	0.84	V_{S3}
3	45	25	6.5	7.5	0.83	V_{S2}
4	42	24	6.5	7.0	0.81	V_{S1}
5	41	24	6.5	7.0	0.75	V_L
$\overline{P}$	47	25	6.8	7.4		
V_R	52	27	7.1	7.8	0.78	
V_E	58	28	7.4	8.3	-	
V_{CR}	49	26	6.9	7.7	0.92	
V_{CL}	44	25	6.6	7.2	0.88	

From the Table VII, V_{CL1} is greater than V_{L1}, the massive contraction of process variables will be defined and repeated by a new rank then the V_{CL1}, V_{CR1} and V_{L1} were selected instead of new V_{S3} and V_{S1} and V_L. The experimental results can be determined the optimal response based on V_{CR} (Table VIII). The preferable levels of process variables by integrated approach of steepest ascent and modified simplex methods are summarized in Table IX.

TABLE IX
PREFERABLE LEVELS OF INFLUENTIAL PROCESS VARIABLES FROM THE FIRST AND SECOND SCENARIOS

Process variables	Description	Operating condition		
		Current	SAM	MSM
X_1	Lapping time	60	48	49
X_2	Lapping speed	30	26	26
X_3	Downward pressure	8.0	7.0	6.9
X_4	Charging pressure	8.0	7.5	7.7

From the process settings for all influential process variables in Table IX, the performance after the improvement of two phases can be evaluated from the desirability levels. Based on the confirmation data, it has been found that the average of the responses from the scenarios 1 and 2 is greater than the current operating condition which can be explained by the box-whisker plot (Fig. 5).

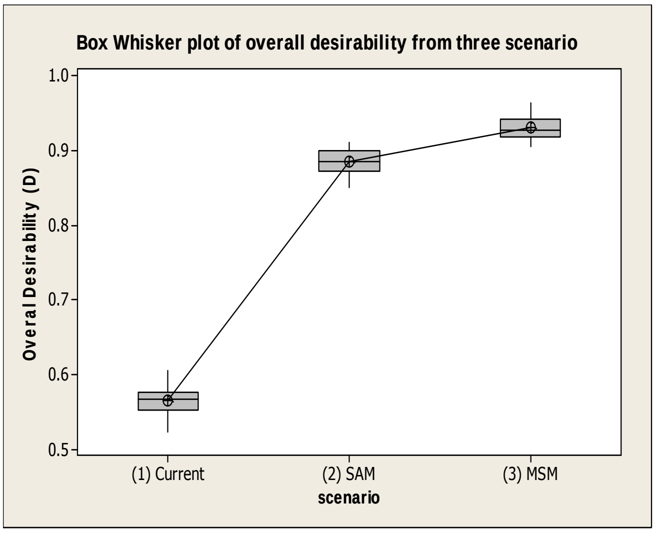

Fig.5 Box-Whisker Plot of Overall Desirability Level from Three Scenarios

ANOVA is a confirmation technique for analyzing experiment data in which a response of overall desirability is measured under various operating condition. It can also be seen that these experimental results on all scenario were statistically significant with 95% confidence interval in Table X. The numerical results suggested that scenario 2 provided the better performance in term of the average of desirability tolerance (Fig. 6). The goodness of the linear statistical model via experiment error or residuals is also adequate in Fig. 7. As the results, scenario 2 is then applied to the lapping process under a consideration of the optimum condition.

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TABLE X
ONE WAY ANOVA: DESIRABILITY VERSUS SCENARIO

Source	DF	SS	MS	F	P-value
Regression	2	1.5769	0.7884	2239.09	0.000
Residual Error	57	0.0200	0.00035		
Total	59	1.5970			

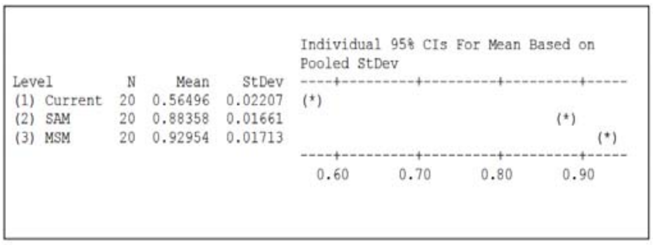

Fig. 6. Graphical Comparison for Three Scenarios

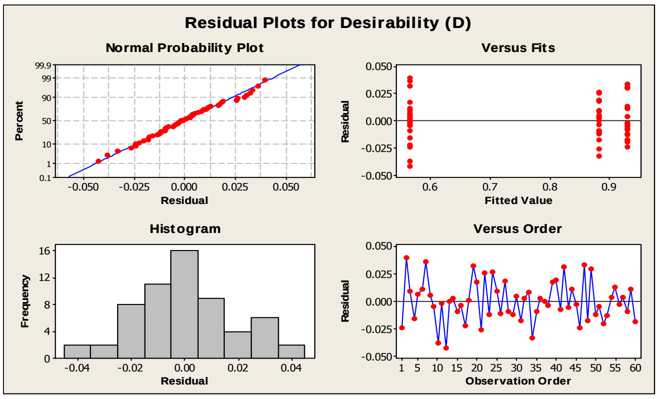

Fig. 7. Model Adequacy Checking

V. CONCLUSION

In this research there are three responses to be considered in order to achieve their targets. The desirability function for a nominal-the-best was applied to compromise multiple responses with the integration of the steepest ascent method based on factorial designs and the modified simplex method. The experimental results showed the following notes.

1) The material removal (MR) can meet the process specification and achieve the proper lap width dimension from the customer specification. It can be said the proper process specification of material removal can be used to predict the lap width dimension as required by customers. The optimal levels of process variables are the lapping time at 49 sec, lapping speed at 26 rpm, downward pressure at 6.9 psi and charging pressure at 7.7 psi.

2) The improvement of clamp force slightly increases with decreased lapping time, lapping speed, downward pressure and charging pressure. This phenomenon is more noticeable against the direction of material removal to achieve the lap width dimension. It means that there are other process variables with somewhat more influence. For the free-state height, body angle and hardness of work pieces these need to be under a consideration and could be more important to achieve the proper value. The free-state height of work pieces should be recommended to set a bit higher than the current one in order to bring the clamp force to, at least, near the optimal point or its target.

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