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Optimization of CNC Laser Cutting Process Parameters

N.Abhimanyu[1], Dr. B. Satyanarayana[2]

M.Tech. Student, VNR Vignana Jyothi Institute of Engineering & Technology, Bachupally, Hyderabad, India[1]

Professor of Mechanical Engg., VNR Vignana Jyothi Institute of Engg., & Technology, Bachupally, Hyderabad, India[2]

Abstract: Laser Beam Cutting (LBC) is one of the largest applications of lasers in metal working industry using thermal energy based non-contact type of machining offering advantages such as high speeds, high quality edges, low-heat input, and minimal work piece distortion successfully used for the cutting of conductive and nonconductive difficult-to-cut advanced engineering materials such as reflective metals, plastics, rubbers, ceramics and composites [1][2]. The pursuit of any machining process is established by determining the equitable aggregate of input parameters. This paper deals with optimization of cut quality during pulsed CO_2 laser cutting of mild steel. In the present paper, various input process variables such as laser power, cutting speed and material thickness are considered for evaluation of the process [3]. The cut quality attributes like Edge Surface Roughness (Ra) and Surface Hardness are considered as output parameters. In view of the effects of machining parameters on the Hardness and Ra, the problem is systematized as optimization problem. The optimum solution is achieved by using suitable statistical method.

Keywords: pulsed CO Laser cutting, Edge Surface Roughness (Ra), Surface Hardness, cutting speed

I. INTRODUCTION

Laser cutting finds many applications in various manufacturing industries where a variety of components in large numbers are required to be machined with high quality and close tolerance at low costs. Numerous additional advantages such as: convenience of operation, high precision, small heat-affected zone, minimum deformity, low waste, low level of noise, flexibility, ease of automation along with technological improvements in laser machines, made laser cutting technology more prevalent in today's production systems. Finally, this technology was found to be suitable for processing a wide variety of materials [4].

Laser cutting is a complex process characterized by a number of parameters which in turn determine the efficiency of the whole process in terms of productivity, cut quality and costs [5]. Maximization of the productivity and the cut quality along with costs minimization are of particular interest to manufacturers. With a limited theoretical and practical background to assist in systematical selection, laser process parameters are usually chosen on the basis of handbook values, manufacturer recommendations and/or previous experience [6]. Above all, optimal cutting parameter settings for achieving a desired goal are not guaranteed [7]. Improper selection of cutting parameters cause high manufacturing costs, low product quality and high waste. On the other hand, the proper selection of these parameters results in improved end product quality.

II. DESIGN OF EXPERIMENTS

A. Cutting process parameters

Process parameter optimization has been widely used in cutting operations. The process parameters affecting the characteristics of turned parts are: cutting tool parameters – tool geometry and tool material; work piece related parameters metallography, hardness, etc.; cutting parameters- cutting speed, cutting power, depth of cut, dry/wet cutting. Singh and Kumar constructed a fishbone cause and effect diagram which was identified the process parameters that may affect the machining characteristics of turned parts and it is shown in Fig.1.

B. Response Surface Methodology

Response Surface Methodology (RSM) focuses a well-known up to date approach on the optimization of the input parameters models based on physical experiments, simulation experiments and experimental observations. These approximated models need to be assessed statistically for their adequacy, and then they can be utilized for an optimization of the initial model. RSM also quantifies relationships between the controllable input parameters and the obtained response surfaces. The input parameters are sometimes called independent variables, and the performance measure or quality characteristic is the response.[8]. By using the results of a numerical experiment in the points of orthogonal experimental design, response surface analysis is computationally much less expensive than a solution using the traditional method. With this analytical model, the objective function problem can be easily solved and also a great deal of the time in computation can be saved. At most, response surface methodology problems have a functional relation between responses and independent variables, and this relation can be explained using the second-order polynomial model.

$$\eta = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_i \sum_j \beta_{ij} X_i X_j + \varepsilon \qquad (1)$$

Where η is the estimated response (surface roughness), β_0 is

Constant, β_i, β_{ii} and β_{ij} represent the coefficients of linear, quadratic, and cross product terms, respectively. X reveals the coded variables.

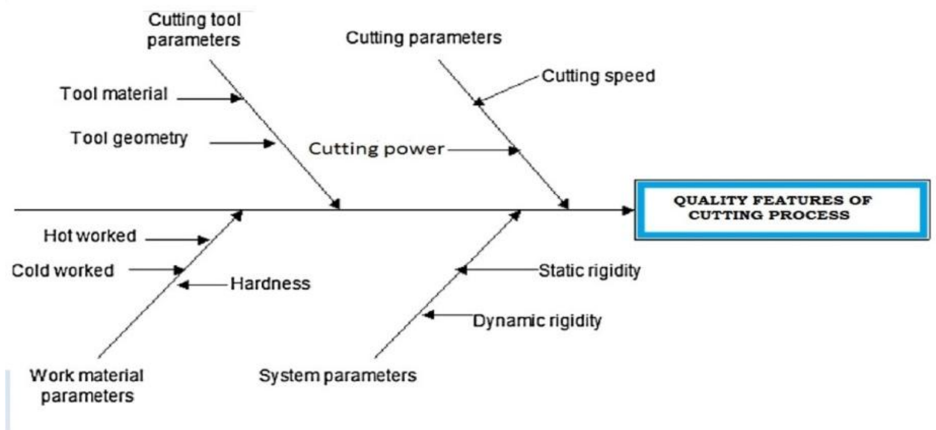

Fig. 1 Fish bone Diagram

The common approach in the RSM is to use regression methods based on least square methods. The method of least squares is typically used to estimate the regression coefficient, which is shown in the following equation.

$$\beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \cdots \\ \cdots \\ \beta_n \end{bmatrix} = \left(X^T X\right)^{-1} X^T \eta = \left[\frac{1}{k}\sum_{j=1}^{k}\eta_j, \frac{\sum_{j=1}^{k} X_{1j}\eta_j}{\sum_{j=1}^{k} X_{1j}^2}, \ldots, \frac{\sum_{j=1}^{k} X_{nj}\eta_j}{\sum_{j=1}^{k} X_{nj}^2}\right]^T \qquad (2)$$

n is the number of objective function and k is the number of factors. The β terms comprise the unknown parameter set which can be estimated by collecting experimental system data. These data can either be sourced from physical experiments or from numeric experiments. The parameter set can be estimated by regression analysis based upon the experimental data [8].

C Taguchi Design

The Taguchi method is a powerful and efficient design of experiment technique, which can improve process performance with a minimum number of experiments. It reduces, rework costs, manufacturing and cycle time costs in processes. The Taguchi design is to find optimal values of the objective function in manufacturing processes. Compared to traditional experimental designs, the Taguchi method makes use of a special design of orthogonal array (OA) to examine the quality characteristics through a minimal number of experiments. The experimental results based on the OA are then transformed into S/N ratios to evaluate the performance characteristics. Therefore, the Taguchi method concentrates on the effects of variations on quality characteristics, rather than on the averages. That is, the Taguchi method makes the process performance insensitive to the variations of uncontrollable noise factors [8]. The optimum parameter conditions are then determined by performing the parameter design. Parameter design is also commonly referred to as robust design. The flowchart of the Taguchi method is illustrated in Fig.2.

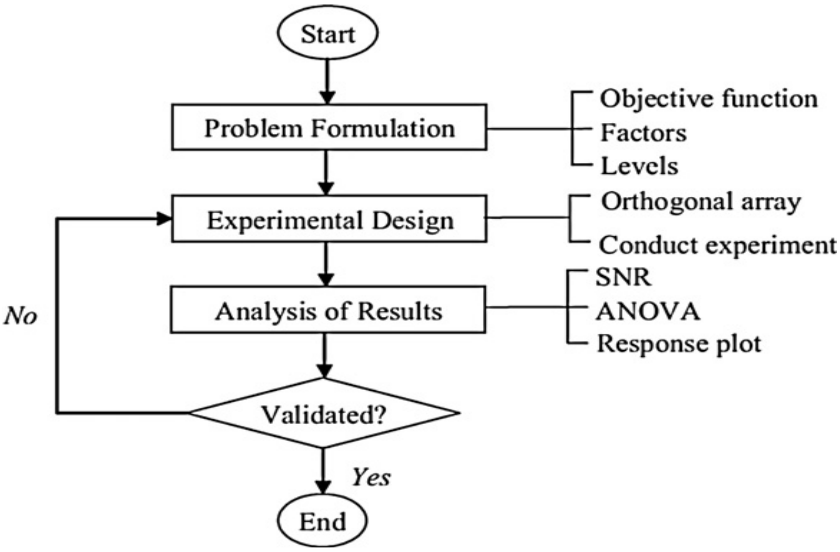

Fig. 2. Taguchi method Flow chart

In this study, therefore, the Taguchi method is employed to determine the optimal turning process parameters. The configuration of the orthogonal array is based on the total degree-of-freedom for cutting ($\boldsymbol{DoF_c}$) of the objective function. The most suitable array is $L_9(3^2)$(standard three level orthogonal array), which needs 9 runs and has 8 $\boldsymbol{DoF_c}$. To check the $\boldsymbol{DoF_c}$ in the experimental design for the three levels of the test, the two main factors take 4 $\boldsymbol{DoF_c}$ s (2× 2) and the remaining $\boldsymbol{DoF_c}$ s are taken by interactions.

III. EXPERIMENTAL PROCEDURE FOR CUTTING

A. Selection of factors and their levels

The literature survey and accordance with the cutting parameters and their levels for the experiment. Finally, three parameters such as cutting speed, feed rate and depth of cut are selected and, the experimental conditions have been given in Table 1.

Table 1 Cutting parameters and their level for cutting

Symbol	Control factor	Units	Level 1	Level 2	Level 3
V	Cutting speed	Mm/min	1000	1100	1200
Watts	Cutting power	Watts	1600	1800	2000
T	Thickness	mm	5	5	5

B. Material and Method

The experimental work was carried out on the LASMAC CNC laser cutting machine (CO_2 laser). Mild steel plate (40mm × 40 mm) was used for the experimentation. The chemical composition of mild steel by (wt %) is given as follows C-0.16, Si-0.03, Mn-0.32, S-0.05, P-0.2, Ni- 0.01, Cu 0.01, Cr-0.01 and Fe. The experimental setup is shown in Fig. 3.

After every experiment, the surface roughness values Ra were measured by Taylor/Hobson precision Surtronic 3+ surface roughness tester and Hardness is measured by Krystal Elmec- Rockwell hardness Tester at B scale at 100 kgf load for mild steel. The measurements were repeated 3 times. Using $L_9(3^2)$ Taguchi standard orthogonal array the experimental results are given in Table 2.

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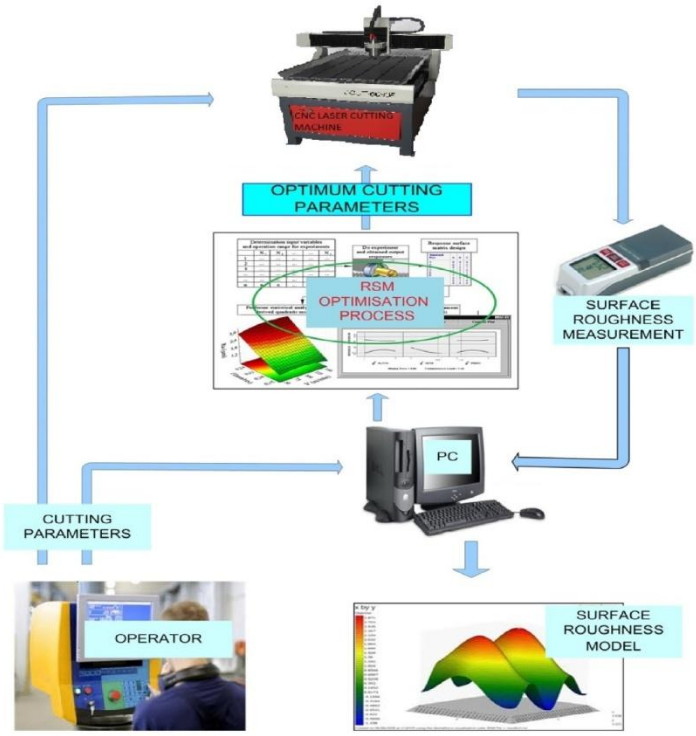

Fig. 3 Experimental set up to measure the response of the process

Table 2 L_9 (3^2) Orthogonal array Experimental details

Exp. No.	Control factors		Edge Ra (microns)	Hardness (HRB)
	Power (watts)	Speed (mm/min)		
1	1600	1000	1.8911	42
2	1600	1100	2.0611	41.055
3	1600	1200	2.2311	40.638
4	1800	1000	1.492	42.602
5	1800	1100	1.631	42.497
6	1800	1200	1.775	42.306
7	2000	1000	1.139	43
8	2000	1100	1.232	43.728
9	2000	1200	1.349	44.332

C. Analysis and Discussions

Table 3 shows the Analysis of Variance (ANOVA) for Edge surface roughness Ra. It can be found that the cutting power and cutting speed are the significant cutting factors for the edge surface roughness. The changes of the cutting power and cutting speed have insignificant effects on edge surface roughness Ra.

Table 4 shows the Analysis of Variance (ANOVA) for Hardness (HRB). It can be found that the cutting power and cutting speed are the significant cutting factors for the Hardness. The changes of the cutting power and cutting speed have insignificant effects on surface Hardness tested by Rockwell Hardness test at B scale represented by HRB.

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Table 3 ANOVA for Edge Ra

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	1.13118	0.377060	2476.99	0.000
Power (watts)	1	0.00009	0.000093	0.61	0.471
Speed (mm/min)	1	0.00911	0.009113	59.86	0.001
Power (watts)*Speed (mm/min)	1	0.00423	0.004225	27.75	0.003
Error	5	0.00076	0.000152		
Total	8	1.13194			

Table 4 ANOVA for Hardness

	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	10.8776	3.62586	236.18	0.000
Power (watts)	1	1.2559	1.25591	81.81	0.000
Speed (mm/min)	1	1.8320	1.83200	119.33	0.000
Power (watts)*Speed (mm/min)	1	1.8144	1.81441	118.19	0.000
Error	5	0.0768	0.01535		
Total	8	10.9543			

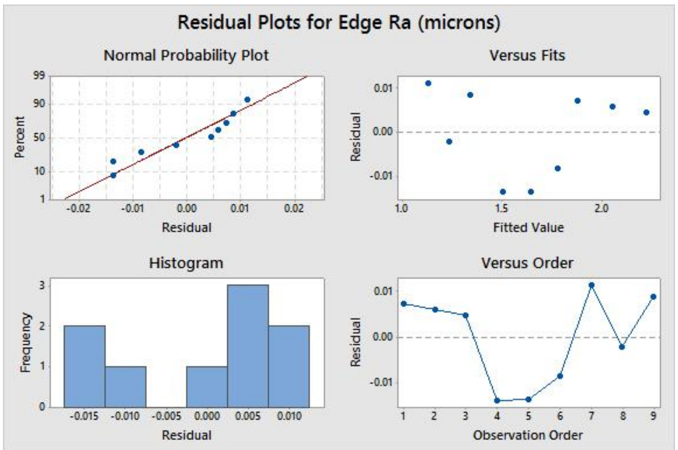

Fig. 4. Residual Surface plots for Edge surface roughness (microns)

D. Prediction optimal performance

The values of the significant factors for Surface roughness Ra and Hardness were given in the Figs. 4 and 5 and Tables 3 and 4 can be used to estimate the mean surface roughness with optimal performance conditions. Two factors were found to be significant in Residual Plots and analysis of variance that is cutting power (Watts) and cutting speed (mm/min), which gave the smallest roughness values and high Hardness. When surface roughness Ra is considered, from Table 5, an estimated average when the two most significant factors are at their better level is at V_3P_3 i.e., at Cutting speed 1200 mm/min and Cutting Power 2000 Watts.

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The figure 6 gives the optimized graph or solution for edge surface roughness and Hardness number where the result is influenced by cutting parameters like cutting power and cutting speed. These parameters play a vital role in the multi response optimization of CNC laser cutting process.

The optimize solution with small edge surface roughness and larger the Hardness value. This solution is based on the two responses in which one includes Smaller the better S-type i.e., edge surface roughness Ra (micro meters or microns) and the other one is Larger the better i.e., Hardness (HRB) value. The optimum cutting parameters are cutting power 2000 (Watts) and Cutting speed 1200 (mm/min).

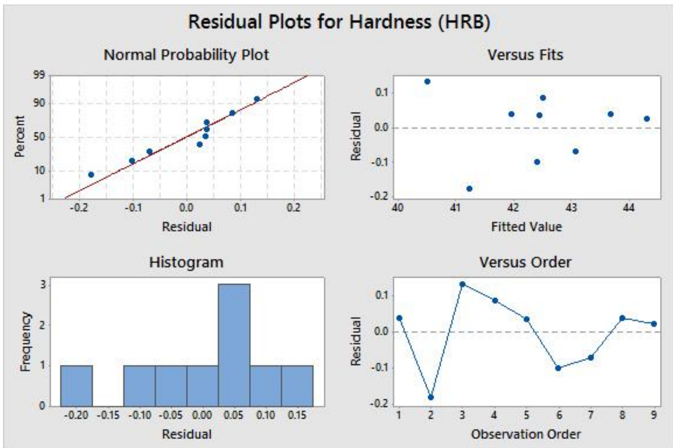

Fig. 5. Residual plots for Hardness (HRB)

E. Response Surface Analysis

The adequacy of the response surface quadratic model was further justified through ANOVA. It reveals that the first-order of Cutting power and cutting speed (a) have significant effects on the Ra and Hardness. On the contrary, the third-order of cutting speed (V) and cutting power pairwise interactions of cutting speed and cutting power have no significant effects on the roughness parameters.

Central composite design was used to develop a correlation between the cutting conditions and roughness parameters Ra and hardness. The quadratic response surface model depicting the roughness parameters can be expressed as a function of cutting factors such as cutting power and cutting speed.

Regression Equation for Edge surface roughness (Ra)

Edge Ra (microns) = 0.595 - 0.000265 (watts) + 0.004313 (mm/min)- 0.000002 (watts)*Speed (mm/min) (1)

Regression Equation for Hardness (HRB)

Hardness (HRB) = 98.69 - 0.03090 (watts) - 0.06116 (mm/min) + 0.000034 (watts)*Speed (mm/min) (2)

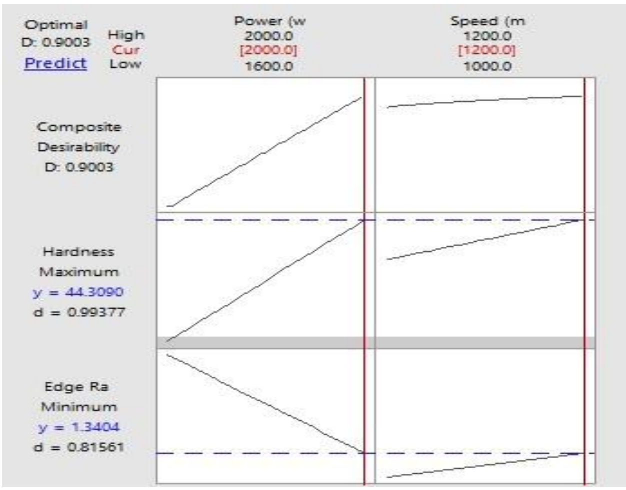

Fig. 6 Optimization Plot

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These figures indicate that the quadratic models are capable of representing the system under the given experimental domain. In order to better understand the interaction effect of variables on roughness parameters, three-dimensional (3D) plots for the measured responses were created based on the model equations (Eqns. (1) and (2)). Since each model had three variables.

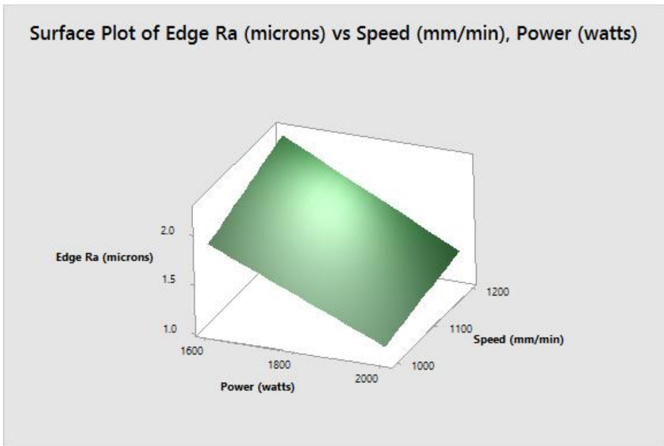

Fig. 7 Surface plots for Edge Ra (microns)

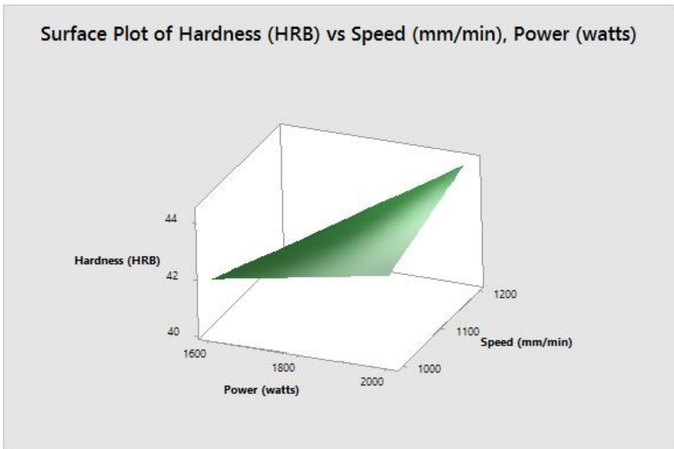

Fig. 8 Surface plots for Hardness (HRB)

IV. CONCLUSION

This Experimental study presented a combined application of the Taguchi method and the RSM to develop a robust CNC Laser Cutting. For this purpose, the first step in the optimization process is to determine the residual plots for all the experimental tests using the Taguchi method. The next step is to find out the objective function. The objective function is formulated using the RSM. The two machining performance characteristics are optimized to meet the objective of the study. According to the results, the following summaries can be made:

i. The Optimized control factors settings for Ra are: $V_{3,}$ (Cutting Speed) 1200 mm/min and P_3 (Cutting Power) 2000 watts
ii. The Optimized control factors settings for Hardness are: V_3 (Cutting Speed) 1200 mm/min and P_3 (Cutting Power) 2000 watts
iii. The RSM was found to be effective for the identification and development of significant relationships between cutting parameters.

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BIOGRAPHIES

N. Abhimanyu was born in the state of Telangana, India. He received the B.Tech. degree in mechanical engineering from Hyderabad Institute of Engineering and Technology, Gowdavelly (Village), Medchal (Mandal), Rangareddy (Dist.) Telangana State, India in 2013 and the M.Tech. degree pursuing in Advance Manufacturing Systems VNR VJIET Hyderabad, Telangana State, India. From 2013 to 2014 he was an Assistant Professor with the Mechanical Engineering Department, NOBLE POLYTECHN -IC COLLEGE, Lingareddypet (Village), Toopran (Mandal), Medak (Dist.), Telangana State, India. He is the member of ISTE.

Dr. B. Satyanarayana (M'72) was born in the state of Andhra Pradesh, India. He received the B.E degree in mechanical engineering from Andhra University, Vizag, Andhra Pradesh, India in 1994 and the M.Tech. Degree - production engineering in 2002, the Ph.D. degree in mechanical engineering from JNT University Hyderabad, Telangana State, India in 2014.

From 1994 to 1998 he was an Assistant Manager with the KCP Ltd and its group. From 1998 to 2006 he was an Assistant Professor, 2006 to 2015, Associate Professor with the Mechanical Engineering Department, VNR VJIET, Hyderabad. Since, 2015 he has been a Professor with the same Department and Institution. He is the author of more than 30 articles. His research interest includes Subtractive and Additive Manufacturing. He is a life member of ISTE and member of ASME. He received the best paper award in IEEE International Conference in 2014. He acted as a conference chair for a few International Conferences.