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ROLE OF RESPONSE SURFACE MODELING IN MANUFACTURING OPERATIONS - AN OVERVIEW

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ABSTRACT

The purpose of the present work is to succinctly overview of recent progress of the role of response surface modeling (RSM) in manufacturing operations such as metal cutting, drilling, turning, milling, welding, machining etc. A significant improvement in the response of manufacturing operations is been obtained by optimizing input cutting parameters with the help of response surface modeling.

Keywords: *Response Surface Modeling, Metal Cutting, Drilling, Turning, Welding and Machining.*

INTRODUCTION

In the year 1951, George E P Box and K B Wilson were first introduced to Response surface methodology (RSM). This is used in statistics to analyze the relationships between explanatory variables and one most responsive variable. The fundamental idea refers to a sequence of a designed experiment to obtain an optimal result. They suggested a second-degree polynomial model to making easy to estimate and apply [1-2]. Development era of the RSM can be categorized in three-part as in 1st (1951-1975), Classical RSM were developed, in 2nd (1976-1999), discussed recently techniques e.g. Taguchi's robust parameter design and in 3rd part (2000 to present) where the methodology are extending with random operations, linear model applications and graphical techniques to compare response surface designs [6].

RSM may classified as First order, second order and mixture model or design depends on the no. of input variables and response of the operation. Polynomial models for a mixture response have less no. of parameters compare than the general polynomial model. This reduction is due to simplex constraints on the mixture components as some terms disappear due to the linear restrictions among the mixture components [7].

Metal Cutting Operation may be performed by using different technologies such as Manual, Machine, welding / burning. In manual technologies, saw, chisel, shear and snips, in machine technologies there are turning, milling, drilling, grinding, sawing, and in welding / burning technologies the laser, oxy-fuel burning, plasma are well known. In a cutting test, tangential forces and surface roughness are the main cutting forces and response variables respectively.

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When using RSM with face centered, central composite design the other input factors investigated are cutting speed, feed rate and the side cutting edge angle of the cutting edge, which are responsible variables of the said forces [9-10].

RSM with Taguchi L9 orthogonal array is used to find the input parameters such as pulse on time, delay time, wire feed speed and ignition current in the cutting operation of Inconel-718 by a brass wire of 0.25mm diameter for the development of artificial neural network (ANN) models and multi response optimization technique for prediction and selection of suitable parameters in wire electro discharge machining (WEDM) operation [16].

In Cryogenic machining, Nitrogen gas is used as a cooling agent in liquid jet form to improve productivity by maintaining hardness and toughness of cutting tool and thus increasing MRR, surface quality, fatigue resistance, compressive residual stresses and white layer characteristics and reduces surface roughness, surface damages with uniform tool wear. It is environmental friendly, safe to use, non hazardous gas and economical too. Thus it can be used for slow grinding to a faster hard turning operation with response surface modeling [19]

Also the nose radius of cutting tool is the main governing factor of the surface roughness during the turning of AISI 1040 steel with Al_2O_3 coated insert tool and 95% effectiveness was found out by using RSM and Taguchi L_{27} orthogonal array [18].

By using Taguchi method found out that cutting speed, depth of cut and feed rate are the input cutting variables during the CNC turning operation to determine the optimal situation and mathematical model for surface roughness of AISI 304 by using carbide insert under dry condition and it is obtained that surface roughness is the function of these cutting variables. This is verified by using the model find out with the help of RSM and by ANOVA. A satisfactory result indicate lower feed rate, lower cutting depth and higher cutting speed for good surface roughness with low % error approx 1% [22].

For metal cutting operation of different shapes, Co_2 Laser cutting method has introduced as a modern and advanced cutting operation, which is performed with the help of CAD graphics. A recent analysis of the effect of Co_2 laser with Ti cutting power and cutting speed on required output of Ti-6AI+4V alloy found out by using lump variables analysis. The quality of the response of this operation depends on selection of process variables with uniform minimum marking of cutting width [43].

Drilling is a cutting operation in which we use drilling tool which is subjected to a point during the operation with aims to make specified hole in the solid object with circular cross section. For the study of this operation with RSM there are many cases to be take in account where the results are optimized for example in case of high speed drilling of carbon fiber reinforced plastic (CFRP) by using cemented carbide (K20) twist drill, damage at the entrance is characterized by delamination factor and which can be reduced by increasing in cutting speed, decreasing the feed rate and better point angle combination and analyze

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by using full factorial DOE with 3 level and developing a non linear regression model based on RSM and tested by ANOVA [5].

RSM model provides optimized results i.e. the predicted and measured output are so close in the drilling of AISI 1045 by using Tin Coated HSS drills. In addition to above a quadratic model developed using RSM to find the accurate response and can be used in prediction of limits of the factors and variables in the operation. RSM approach shows a scientific and positive method for modeling and optimization of such operations [20].

In the drilling operation of Glass fiber reinforced composite by using fuzzy logic, RSM, Taguchi orthogonal array, Pareto – ANOVA and ANOVA gives lowest difference between experimental and actual results. The optimized situation is obtained with ANOVA and response graphs which show limited effect of spindle speed. Therefore the minimum surface roughness can be achieved at high spindle speed, low feed rate and minimum drill diameter [21].

In the drilling operation of steel AISI 316 with PVD coated tools of carbide, investigation of effect of cutting variable and mean square of specimen vibration where vibration is measured by Laser Doppler Vibrometer in the form of Acousto Optic Emission Signals which is processed and transformed in variable frequency regions with use of Fourier Transformation and ANOVA is use to compare identical cutting variables. RSM and ANN with support vector machine were used to define the surface roughness and root mean square of vibration of the specimen. A minimum surface roughness is reported by using a multi response method [26-27].

An earlier competitive review on multi holes drilling operation which aims to improve both quality and productivity as more time needs for motion of tools and switch that. This researcher focused on drilling path optimization where others focused on reduction of time taken by tool motion and switching it. In this way he worked on drilling areas, modeling issues, optimization operation with path optimization. This work is still in growing stage however he suggested in his paper for further to focus on energy consumption in the operation, to explore the Meta heuristics algorithms which may reduce the drilling time or machining time. Here in this study Response surface modeling will be an important and optimized method to find the optimal drilling time as it is able to define the significant level of setting of all possible input variables with ANOVA [42].

Welding is a joining operation of same or different material parts such as metals or thermoplastics by using required quantity of heat to melt along together and cool down due to fusion. For such operation, a mathematical model was developed using RSM for the analysis of effects of direct interactions variables such as open circuit voltage, wire feed rate, welding speed and nozzle to work piece distance on the cladding geometry e.g. depth of penetration, height of reinforcement, weld-width and dilution % for the optimization operation of different welding operation [15].

In the application of RSM during a TIG welding operation, input variables (such as

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input current, welding speed) effected directly7 to the geometry of the weld zone e.g. depth of penetration, bead width, depth to width ratio. While it is noted that flux coating density has negligible effect on welding zone. An optimization is recorded in the above experiment [28].

Since genetic algorithm fails to model the relationship of responsible variables and response so for this work RSM was used to develop the model and optimize weld bead geometry for gas metal arc welding operation [36].

The effect of welding variables (weld time, weld current, electrode force in the fusion zone and heat affected zone, tensile load and shear load) on the weld quality were analyzed by using RSM, and Taguchi L9 orthogonal array in Minitab 17 and found that when the weld time was 0.2 s, weld current 10 KA and the required electrode force was 2.3 KN in a spot welding operation gave good weld quality with 5% discrepancies in these parameters and weld current had 69% contribution which represents weld current is the most important parameter to optimized the RSW joint [37].

By using RSM, an earlier experimental study of 2019 reported that in gas tungsten arc welding when it controlled by a robot and was been building complex three dimension parts by successive layer deposition method, 3 variables (peak current, tool speed, feed rate) were talked for effect analysis of the resulted bead dimensions (height and width) it is found in the experiment that the connectedness extracted between response and input variables simultaneously and also author suggested to will have a positive changes in pre monitoring operation of bead dimensions during the operation [41].

Turning is a machining operation in which by using rotational cutting tool/tools removal of specified undesired material operation is performed. As we know that surface roughness is a common expect in view of quality aspects and also as per technical requirements. The surface roughness is directly proportional to feed rate and inversely proportional to nose radius of the cutting tool in the turning operation with response surface methodology. The verified model shows 5.98% error with predicted output [25].

As turning and/or machining operation is complex operation depends on different parameters such as cooling condition, cutting speed, feed rate and depth of penetration on arithmetic average roughness (Ra) and average maximum height of the profile (Rz).During the turning of AISI 1050 steel, under dry condition, conventional wet cooling and MQL. RSM is used to design a mathematical model for surface roughness with Ra and Rz. It is found that feed rate is so effective on surface roughness, cooling conditions are also effective and MQL is a good tool to increase the surface quality [31].

It is found during the turning operation study of AISI 52100 that surface roughness is effected by feed rate and cutting speed which is affected by the axial cutting force which is highly resist by the hardness of the specimen and sensitive to cut angle and tool wear. And depth of penetration is varies

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according to the cutting forces highly in compare than feed rate and cutting speed [32].

Abrasive Water Jet Turning of Hybrid Matrix Composite Material as having an important application in automobile and aircraft industries requires higher strength to weight ratio, must to have good wear and corrosive resistivity, higher hardness, stiffness and thermal properties cannot produced in mass production due to its critical machining operation. As we know, abrasive particle have higher hardness and hence they requires harder tool with higher wear resistance. With the help of RSM and ANOVA we are able to find the optimum result for operation parameter involving here in this operation and a recent study shows the optimum surface roughness found between 6.0545 micrometer to 8.3825 micrometer and MRR variation obtained as 434.72 mm^3/min to 565.02 mm^3/min by using AWT of hybrid MMC of $A_{359}/B_4C/Al_2O_3$ produced electromagnetic stir casting method [40].

A dielectric fluid used in the electrical discharge machining (EDM) operation by de ionized water. Which acts as a semiconductor between energized wire and the work piece to maintain control and stability of ionization during the spark gap, RSM is a suitable methodology in different kind of experiment of dielectric machining operation such as When SiC powder takes as an additive in the dielectric machining operation of Ti-6246 using response surface methodology results the smaller surface roughness and more MRR due to combination of high peak current and high concentration with the error between experimented and predicted values in MRR is -8% to +8% and in surface roughness is -7.85% to 3.15% respectively [14].

In silicon powder mix electro discharge machining (EDM), concentration of silicon particles in dielectric fluid, pulse rate, duty cycle and peak current are independent parameters by which performance prediction make in terms of surface roughness and MRR. In the above operation a copper electrode with 25 mm diameter is used for cutting of EN 31 steel work piece on EZNC fuzzy logic. RSM is used to find out the effect of those independent parameters on the resulted surface roughness to make a prediction of required model. Non sorted genetic algorithm (NSGA) is used for optimization of results [23].

In an earlier article as discussed in diamond grinding dielectric discharge machining used as a hybrid machining operation which able to improve the material removal rate while it is difficult to machining of super alloys ceramics and other composite materials which come possible by the help of RSM. As it is experimentally proved by developing a model for diamond grinding using electric discharge marching operation of titanium nitride aluminum oxide ($TiNAl_2O_3$) where RSM explores characteristics of the operational parameters with seven centered pointed face centered composite rotatable design. In this experiment it did noticed that micro cracks and micro pores are diminished on the workout surface and material removal rate is optimized when wheel speed, peak current, pulse time and duty factor keeps as

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controllable factors and material removal rate taken as response plus obtaining regression equation for MRR and MRR are analyzed using RSM [44].

The Fused Deposition Modeling (FDM) is a three dimensional printing technique and Fused Filament Fabrication (FFF) is comes under FDM have many application such as 3D printing, Plastic Jet Printing, Material extruding etc. In this operation need to created a STL file of the model with the help of graphic design computer software first with found optimum setting of parameters by the help of RSM and it need to imported into Stratasys which is a software which is able to make slices into horizontal layers mathematically and can be generate the desired supports then it creates tool paths as needed for extrusion operation after all the system draws cross sections of the model in 3D coordinate axes system and by using heated material extrusion process performed and hence 3D printing obtained. In such a way uses of RSM in different kind explain as per earlier researches as one is compressive stress decreases with increases in the number of layers and the deposition of same cross sectional layer reduce the distortion in case of fused deposition modeling (FDM), which properties can be improved by setting of variables at suited situation. The above setting also provides complex dependency of comp. stress and develops a valid prediction of the model. By which and through quantum-behaved particle swarm optimization (QPSO) we can find optimized variable setting [24]. FDM operation was introduced by Stratasys Inc. USA in 1990. The quality of FDM processed response varies with selection of operation variables so the selection of FDM operation parameters is important [38].

For dimensional improvement of part extruded by fused deposition modeling when desirability is PCA based the optimization operation suggests that fabrication operation should be performed with raster angle be 30^{o}, raster width for minimal relative changes in length, width, and thickness be 0.4064 mm where response surface methodology based face centered central composite design is used for designing and modeling of the experiment and ANOVA is used to analysis of effects of operation parameters. Anderson-darling normality test is used to test the stability of the model. To find the optimal parameter setting for minimum deviation in dimension as a hybrid approach weighted principal component analysis (WPCA) – based desirability method is used [39]

Hemming and seaming are found similar in the way of its working operations. In both the operation a sheet metal edge is rolled over onto itself. These process can be differentiate as in Hemming the edge is rolled flush to itself while in seaming edges of two materials are joins together. In earlier research and development different kind of hemming operations are found as per materials, size of sheets and required geometry. In such way RSM is found to important modeling method of these experiments to optimized the results of the operation for example one of them is Solid to shell modeling with central composite design is used to describes the relationship between basic operational variables and

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hemming dimensions and both material properties in the 3-D hemming operation of a sheet on to itself or another sheet by using Finite element analysis. In this operation key variables are preheating angle on roll - in or roll – out, surface curvature, initial strain in the sheet and flanging die radius etc. [13].

An another earlier research results depends on input parameters, undesired wrinkling formation and hemming forces whichare directly related to material quality and characteristics varies during the operation, bending angle, roller diameter influence on roll in, deformation and sheet thickness in this operation set of mathematical equations model by using RSM and regression analysis for curved edge parts. Where in the experiment roller hamming was used with back forming operation and complex forth and it is find out that sheet thickness is the most responsible variables on roll in operation including plastic strain strength of the sheet material [45]. Hemming operation may results surface defects due to less or uncontrolled behavior on the operational parameters, if we consider the case of fuel tank cap with material $DX_{54}D+Z$ deep drawing steel sheet and mathematical set for RSM respond the operation modeling then the operation is optimized with Taguchi orthogonal array. By using the experiment result optimal hemming operation can be plan. Surface compensation of the geometry of the hamming tool to be based on the curvature characteristics to reduce or eliminate the bad response of the operation as that is undesired [46]

Laser Cladding is a thermal spray operation also it is a weld build – up operation with a complementing coating technology. In this operation the laser beam is defocused on the specimen with a specified spot by using of laser optics and powder nozzle which is moves across the surface of the specimen. This operation is useful in joining of one material to another in a controlled behavior. A stream of needed powder is fed in to the doused laser beam to scan across the target surface, hence making deposited coating of the selected material. Thus this is an additive manufacturing operation in which material deposited onto. RSM is used in the manner of designing and modeling of such experiments. In case of improper selection of variables during manufacturing operation via Laser Cladding technique results the adverse effect. To build a mathematical model employs central composite design (CCD) and response surface modeling (RSM) for optimizing the quality of coating of Inconel 625 reinforced matrix with tungsten carbide with shielding of gas flow where it is found that energy distribution is a governing factor effect the responses. In above experiment dilution ratio was minimized and efficiency of the operation was maximized by proper distribution of the energy [29].

An experimental research to find the effects of surface roughness and coating of Cr_2O_3 layer on the laser cladding operation has performed earlier as per widely using of laser technology in manufacturing operations such as cutting, surface operations e.g. heat treatment, coating and cleaning etc, welding, forming and prototyping and many more. In the said study investigation of the effects of two

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variable surface roughnesses and Cr_2O_3 layer created on the sheet of AISI 304 Stainless steel. On this way multi objective optimization was performed using different methods and it is validated that RSM gives the good optimization in the response as a result of surface roughness 0.04 micrometer to 1.9 micrometer without coating and by depositing up to 6 micrometer without roughening, the absorptivity at the laser wavelength is found 1064 nm and hence the bending angle was increased too which could increase the laser light absorption using RSM for design and modeling of the experiment [47].

Multivariate Statistical techniques are used in the analysis of the characteristics of a joint in aspect more than one random variables. In this operations RSM is used to design and modeling for two or more response variables as it attempt to reality where each situation, experiment or decision included more than a single factor. A comparison in terms of characteristics and efficiency of multivariate statistical technique of Symmetrical experimental designs (three-level factorial, Box–Behnken, central composite, and Doehlert designs) is helpful to find the appropriate setting of variables for RSM [4].

A multi response surface methodology (MRSM) can be applied on those processes where a lot of data set is in use and no. of output are in multiple and need to optimize concomitantly. Also the said procedure is easy to use with predefined set of statistical standard [17].

Additionally in such cases one set of sample points can be applied to all response surfaces for example in an experiment of a vehicle four variations of the front wheel positioning variables are taken in account to optimized the response those 4 variable may be design parameters since it is four so there are no. of samples found as sixty, when the RSM is used to design and modeling to optimize the response. The optimization represents reduction in camber angles from 2.0^o to 0.339^o and caster angle increases from 0.49^o to 0.546^o, kingpin inclination angle reduced from 2.46^o to 0.42^o and toe angle increases from -1.47^o to -0.345^o. This is also an example of kinematical system and double wishbone suspension [48].

The hotspot temperature is important response variable in the thermal management of an oil immersed distribution operation of transformer examined numerically using RSM in these operation different geometrical parameters as investigated are thermal properties of transformer oil, geometrical dimensions of the transformer and load applied on the transformer. By using the RSM optimization in response found as reduction in hotspot temperature 15^oC to 17^oC for optimized dimensions and other input variables [49].

Robust design is generally used in product design but also can be applicable in other aspects too, As it is a concept which was introduced by Dr. Genichi Taguchi, According to this phenomenon reduction in variation in a product without eliminating the causes of the variation such as producing the product or making the process with taking the effect of variation or noise factors in account as well as controlled factors. RSM have a great roll in this operation to

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optimize the response in many kinds of products, manufacturing operations and processes too. We can start the analysis with an example of a paper which says that Approximating function will be first order model if the response is well modeled by a linear function of independent variable and it will be second order model if there is a curvature in the system and hence there a higher degree polynomial is used. Designs for fitting response surfaces known as response surfaces designs. RSM is a sequential procedure where the objective is to lead the experimenter rapidly and effectively with improvement in the optimum value of the outputs [7] & [35].

In 1980, Genichi Taguchi introduced parametric design to reduce variation in products and processes by using AT&T Bell Laboratories. By which a response surface method evolved and resulted a collection of tools that allow the adopting of Taguchi's robust design [8].

A second order response surface model with Taguchi Method is useful to reducing the geometrical error. It helps to select the proper grinding conditions with constraints of surface roughness and material removal rate for a grinding operation [12].

To handle noise factors in Taguchi's Approach such as robust design where mean and variance of the responses takes separately (dual response), Box, Jones and Myers described the way to determine these dual response from a UN replicated experiment by using of RSM [34].

In a recent research paper it is obtained that the robust design reduces the sensitivity of the needle bar and thread take up lever mechanism (NBTTL) (which is used in sewing machines) responses to the design variables uncertainties compared with deterministic one. The optimization in the response by finding appropriate setting of variable as per effects of noise factors and taking in account to all controlled variables are possible using response surface methodology to design and modeling of a set of experiments and find the optimized response by analysis of responses using ANOVA. In said operation variables may be transmission angle, couple tracking error and standard deviation with design variables uncertainties [50].

This operation represents the prototyping before making models and going for physical experiment by helping the advance available resources such as computer, software and simulation system to find the predicted response without doing the actual experiment to save the cost, time, manpower and leave the chances of different kind of risk which can be happen. Today it is widely used and has greater optimization, RSM also is helpful to design and modeling of such kind of operation to find the optimal and nearer or actual prediction of the responses with different setting of variables with negligible cost and no losses in compare than actual experiments. Simulation and optimization of operational design of a supply chain system-RSM with Taguchi techniques is an effective tool which make possible to understand the dynamic relations among various factors and can reduce the demand uncertainty of a supply chain system [11].

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By using infrared radiation to intensify the properties of Reutealistrisperma for the production of biodiesel, an earlier research represents validate simulation with optimization. Where Reutilize trisperma is a non edible vegetable oil with high content of fatty acid and Infrared radiation is lower energy consumption operation to provide the necessary heat as per requirements of the said operation. An optimized response is obtained when it design and model using RSM and analyze using ANOVA by comparing with ASTMD6451 and EN14214. The exact optimized response is recorded by the experimenter is predicted 98.39% where actual is 97.78%. In this operation process variables were found as the reaction temperature, methanol to oil molar ratio, reaction time and catalyst concentration. To validate the quadratic model experiments performed in triplicate form. Hence it can be say that absolutely it is a great achievement of the Response Surface Modeling in the field of simulation and optimization [51].

METHODOLOGY

Response Surface Modeling (RSM)is a mathematical and statistical method use for design, modeling and analysis of problems, relations and effects on response of several variables and factors. Its working operation can understand through an example discussed as below:

Suppose that a chemical operation as we know that a chemical operation mainly depends on the temperature and pressure suppose as same for a particular chemical operation and let temperature be T and pressure is P and then the yield point of the operation where the chemical operation gives the best response. Thus the yielding of the chemical operation can be written as,

$y = f(T, P) + e$

Where f represents response function in two variables temperature (T) and pressure (P) and here e represent the noise or error observed in the response y.

If we ignore the error then the expected response can be written as,

$E(y) = f(T, P)$

This is an equation of a surface, known as **r**esponse surface for respective operation**.** For example as below we shown the 3D plot of oxygen self diffusion chemical operation due to variation in temperature and pressure under limit.

Mostly the form of the relationship between independent variables and response are found unknown so firstly approximation of true functional relationship between y and set of independent variables to be find out. For this work we use different type of polynomial equation as per requirements. If the response is a linear function of the independent variable then there is first order model is applicable. And if there is a curvature in the system then a polynomial of higher degree must be used e.g. second order model.

In addition, in starting case when the optimum response is so for from the actual for the experiment we suggest to use simple and economically efficient procedure like as method of steepest ascent to move sequentially in the direction of optimum response and if minimization is desired method of steepest descent is preferred.

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When the optimum is relatively close to the actual i.e. the experiment has curvature required to approximation of the responses for this case second order model is preferred. (For details of methods and process of the analysis read Chapter 11 of Design and Analysis of experiments of Douglas C. Montgomery, 2012)

LIMITATION OF RSM

A hybrid response surface (HRS) refers to a multi objective with a large no. of variables having manufacturing operation optimization where can employ analysis of characteristics of transient thermal variable with high thermal loads, hear transfer coefficient, thermal resistance. When use HRS for a ball screw feed drive system simulation error of the temperature field reduced from 25% to 10% and simulation error for thermal elongation reduced from 30% to 11% [30].

In the modern applications traditional assumptions of RSM results error distribution and the model not necessarily valid while generalized linear models (GLMs) are best suited to these types of situation. GLMs included three components one is response vector, which is a member of exponential family and distributed independently according to the certain distribution law. Second component is linear predictor, which is polynomial function in control variables and third is a link function which related to the mean response of polynomial function at a given point in a specified region. The iterative weighted least squares procedure is use in GLMs for analysis [2].

RSM is limited by selection of the replicates as if taking a higher polynomial order system then the number of mathematical equation increases and with RSM something is trouble to design and modeling of that system. As we know that it is first introduced for biochemical process but due to its development in large it evolves in a large no. of fields as per requirements and its effectiveness in compare than other or not availability of suitable method to find optimized response. Hence during this development era some limitation getting attached with RSM as specified in some research articles about its estimation and easiness to work for a critical system etc. Hence if we need to analyze the reliability of a heavy and complex structure the RSM is limited to give a valid response in latest technology as now available finite Element Analysis and computational analysis computer software which gives more accurate response compare than RSM. Since Response Surface approach mean variance and standard deviations to increase the efficiency which may have large calculation and time consumable and in such cases probability of calculation errors may also higher. In these kinds of cases sometimes we can use Mont Carlo Simulation techniques to get desired reliability estimates [3].

CONCLUSION

Role of Response Surface Modeling has been recognized as it is found a very important method for design and modeling of an experiment to improving quality, performance and other output responses (if any) of different kind of manufacturing operations. The development of more

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effective, statistical efficient, and user friendly experimental modeling methods will allow to experimenter to effectively plan the experiment and effectively analyze the observed data by themselves. This work reviewed newly developed statistical methods for different manufacturing operation and identified areas so the reader would benefit more and thus the use of RSM for quality and performance improvement of the manufacturing operations increases.

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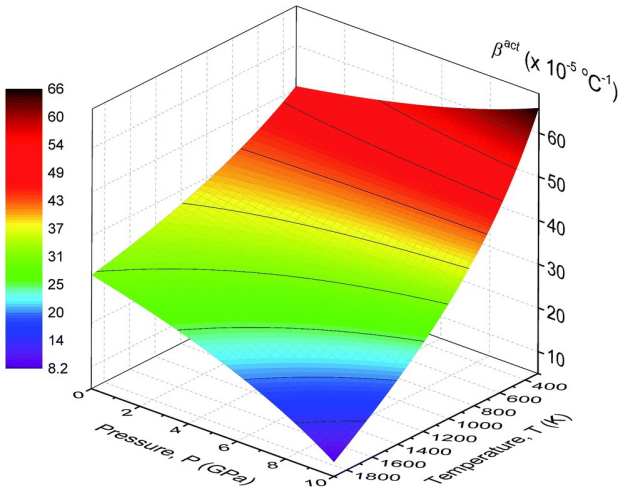

Fig.1: *The thermal expansion coefficient of the activation volume β^{act} - 3D surface plot, as a function of temperature (300–1900 K) and pressure (0–10 GPa) for oxygen self diffusion [33].*