International Journal of Enhanced Research in Science Technology & Engineering, ISSN: 2319-7463
Vol. 2 Issue 7, July-2013, pp: (83-89), Available online at: www.erpublications.com

Optimization of cutting parameters for turning operations based on response surface methodology

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Abstract: This paper presents the findings of an experimental investigation into the effects of cutting speed, feed rate, depth of cut, nose radius and cutting environment in Lathe turning of mild steel tool. Design of experiment techniques, i.e. response surface methodology (RSM) has been used to accomplish the objective of the experimental study. Face centered central composite design have been used for conducting the experiments. 3D surface plots of RSM revealed that cryogenic environment is the most significant factor in minimizing power consumption followed by cutting speed and depth of cut. The effects of feed rate and nose radius were found to be insignificant compared to other factors. Though both the techniques predicted near similar results, RSM technique seems to have an edge over the Taguchi's technique.

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1. INTRODUCTION

Machine tool technology is often labeled as "Mother Technology" in view of the fact that it provides essential tools that generate production in almost all sectors of economy. It is of prime importance not only to the machine tool industries but also to the entire class of engineering manufacturing industries using machine tools in one form or the other. Even though the machine tool industry in India has made tremendous progress, the metal cutting industries using various machine tools continue to suffer from a major drawback of not utilizing the machine tools at their full potential. A major cause leading to such a situation is thought to be the failure to run the machine tools at their optimum operating conditions. The problem of arriving at the optimum levels of the operating when using the machine tools has attracted the attention of the research workers and practicing engineers for a very long time.

The selection of optimal cutting parameters, like the number of passes, depth of cut for each pass, feed and speed, is a very important issue for every machining process. In workshop practice, cutting parameters are selected from machining databases or specialized handbooks, but the range given in these sources are actually starting values, and are not the optimal values (Dereli et al., 2001).

Optimization of cutting parameters is usually a difficult work (Kumar and Kumar, 2000), where the following aspects are required:

1. Knowledge of machining.
2. Empirical equations relating the tool life, forces, power, surface finish, etc., to develop realistic constrains, specification of machine tool capabilities.
3. Development of an effective optimization criterion, knowledge of mathematical and numerical optimization techniques (Sonmez et al, 1999).

In any optimization procedure, it is a crucial aspect to identify the output of chief importance, the so-called optimization objective or optimization criterion.

2. MECHANICS OF CUTTING

Turning is the process whereby a single point cutting tool is parallel to the surface. It can be done manually, in a traditional form of lathe, which frequently requires continuous supervision by the operator, or by using a computer controlled and automated lathe which does not. When turning, a piece of material, it is rotated and a cutting tool is traversed along 2 axes of motion to produce precise diameters and depths. Turning can be either on the outside of the cylinder or on the inside (also known as boring) to produce tubular components to various geometries.

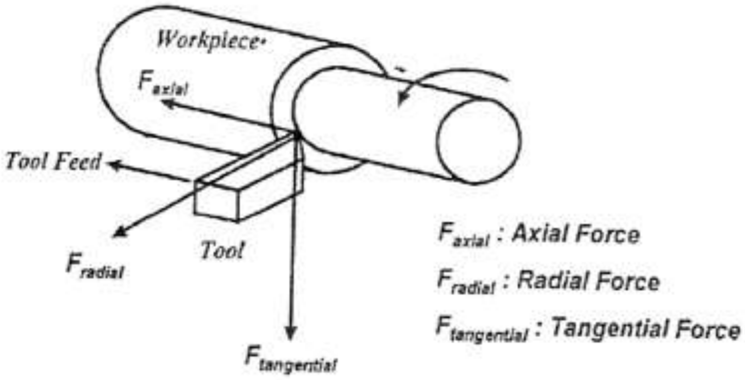

Figure 1: Principle Forces in Bar Turning (Melkote, 1999)

The turning processes are typically carried out on a lathe, considered to be the oldest machine tools, and can be of four different types such as:

1. Straight turning,
2. Taper turning,
3. Profiling,
4. External grooving.

Those types of turning processes can produce various shapes of materials such as straight, conical, curved, or grooved work piece. In general, turning uses simple single-point cutting tools.
Each group of work piece materials has an optimum set of tools angles which have been developed through the years. The bits of waste metal from turning operations are known as chips (North America), or swarf (Britain). In some areas they may be known as turnings.

3. DYNAMICS OF TURNING

The relative forces in a turning operation are important in the design of machine tools. The machine tool and its components must be able to withstand these forces without causing significant deflections, vibrations, or chatter during the operation.

3.1 Principal Forces

During a turning process basically there are three principal forces as shown in Fig. 1.1 and discussed below:

1. The Cutting or Tangential Force acts downward on the tool tip allowing deflection of the work piece upward. It supplies the energy required for the cutting operation.
2. The Axial, Thrust or Feed Force acts in the longitudinal direction. It is also called the feed force because it is in the feed direction of the tool. This force tends to push the tool away from the chuck.
3. The Radial Force acts in the radial direction and tends to push the tool away from the work piece.

3.2 Primary Factors

The three primary factors in any basic turning operation are speed, feed, and depth of cut (Figure 1.2). Other factors such as kind of material and type of tool have a large influence, of course, but these three are the ones the operator can change by adjusting the controls, right at the machine.

1. Speed, always refers to the spindle and the work piece. When it is stated in revolutions per minute (rpm) it tells their rotating speed. But the important figure for a particular turning operation is the surface speed, or the speed at which the work piece material is moving past the cutting tool. It is simply the product of the rotating speed times the circumference (in feet) of the work piece before the cut is started. It is expressed in surface feet per minute (sfpm), and it refers only to the work piece. Every different diameter on a work piece will have a different cutting speed, even though the rotating speed remains the same.

2. Feed, always refers to the cutting tool, and it is the rate at which the tool advances along its cutting path. On most power-fed lathes, the feed rate is directly related to the spindle speed and is expressed in inches (of tool advance) per revolution (of the spindle).

3. Depth of cut is practically self-explanatory. It is the thickness of the layer being removed from the work piece or the distance from the uncut surface of the work to the cut surface, expressed in inches. It is important to note, though, that the diameter of the workpiece is reduced by two times the depth of cut because this layer is being removed from both sides of the work.

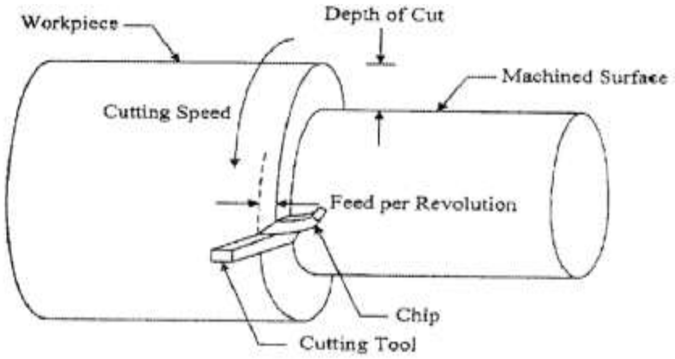

Figure 2: Basic Turning Operation (Tarng,1998)

4. LITERATURE REVIEW

Melkote et. al, (1999) conducted investigation to determine the effects of tool cutting edge geometry and work piece hardness on the surface roughness and cutting forces in the finish hard turning of AISI 52100 steel. Wang (2000) investigated the effect of cutting tool hard surface coatings on the cutting forces while turning a CS1020 mild carbon steel. Lin et. a,l (2001) investigated turning of S55C high carbon steel with a sintered carbide insert and reported that the critical parameter that affect the surface roughness is the feed rate; increasing feed rate will increase the surface roughness value. M.Y. Noordin et al (2002) investigated the performance of a multilayer tungsten carbide tool was described using response surface methodology (RSM) when turning AISI 1045 steel. Cutting tests were performed with constant depth of cut and under dry cutting conditions. Seker et al (2004) studied the effect of cutting speed while turning AISI 304 austenitic stainless steel with multi –layered coated (TiC,TiCN,Al2O3,TiN) cemented carbide inserts having chip breaker grooves. Feed rate, depth of cut and insert geometry were kept fixed.

V.C Venkatesh et. al (2004) investigated the performance of a multilayer tungsten carbide tool using response surface methodology (RSM) when turning AISI 1045 steel. Hasan Gokkayaa et al (2005) investigated the effects of different insert radii of cutting tools, different depths of cut and, different feed rates on the surface quality of the work pieces depending on various processing parameters. Singh et al (2006) reported optimal setting of turning process parameters (cutting speed, feed rate and depth of cut) resulting in an optimal value of feed force when machining En 24 steel with TiC-coated tungsten carbide inserts. Aggarwal et. al (2008) investigated the effects of cutting speed, feed rate, depth of cut, nose radius, and cutting environment in CNC turning of AISI P-20 tool steel with TiN coated tungsten carbide inserts. Aggarwal et. al (2008) optimised the multiple characteristics (tool life, cutting force, surface roughness and power consumption) in CNC turning of AISI P-20 tool steel using Principal Component Analysis (PCA). Lin (2008) studied the surface roughness variation in high speed fine turning of SUS 303, SUS 303 Cu and SUS 304 austenitic steel with disposable cermet turning tool having fixed nose radius of 0.8 mm. It was found that, the smaller the feed rate, the smaller the surface roughness value.

Gandarias et. al (2008) studied the performance of the turning of austenitic stainless steels using two coolant techniques namely the high pressure through the tool spindle and micro-pulverisation of oil in air applied internal to the spindle and Minimum Quantity of Lubricant (MQL). D.I Lalwani et. al (2008) investigated the effect of cutting parameters (cutting speed, feed rate and depth of cut) on cutting forces (feed force, thrust force and cutting force) and surface roughness in finish hard turning of MDN250 steel (equivalent to 18Ni(250) steel) using coated ceramic tool. Jenn-Tsong Horng et al (2008) conducted a series of tests in order to investigate the machinability evaluation of Hadfield steel in the hard turning. Sittichai et al (2009) investigated factors which influenced surface roughness while turning AISI/SUS 304 stainless steel with coated carbide inserts. Speed and feed rate were taken as factors each set at three levels. Factorial design was used and each trial was replicated. The authors reported that only speed factor affected surface roughness for turning stainless steel.

Basim A. Khidhir et. al, (2009) investigated the machinability of nickel based Hastelloy C-276 in turning operations using ceramic inserts under dry conditions. Hastelloy C-276 is a difficult-to-machine material because of its low thermal diffusive property and high strength at high temperature. Khaider Bouacha et. al (2010) conducted an experimental study on hard turning with CBN tool of AISI 52100 bearing steel, hardened at 64 HRC. B. Fnides et. al, (2010) conducted this experimental investigation to determine statistical models of cutting forces in hard turning of AISI H11 hot work tool steel (~ 50 HRC). A. Y. Mustafa et al, (2011) analysed the geometric tolerance and surface quality of an aluminium piece produced by turning. Nilrudra Mandal et al (2011) investigated the influence of factors such as cutting speed, feed rate and depth of cut on flank wear during hard turning of EN 24 steel with newly developed transformed toughened nano-composite Zirconia Toughened Alumina (ZTA) ceramic inserts. Suleyman Neseli et. al, (2011) investigated on the influence of tool geometry on the surface finish obtained in turning of AISI 1040 steel.

5. DESIGN OF EXPERIMENT TECHNIQUES

5.1 RSM: A statistical tool for process optimization

The classical approach to experimental planning (one-at-a-time designs) involves many effort and time and in some cases, where factor interactions take place, it is by far inapplicable. The most efficient way to enhance the value of research and to cut down the time in process development is through experimental designs. The statistical experiment designs most widely used in optimisation experiments are termed "response surface designs". Response surface methodology is an approach to product and process optimisation work, derives its name from the use of these widely used optimisation experiment designs.

Response Surface Methodology (RSM) was introduced by Box and Wilson in 1951 and later popularised by Montgomery. As per the introducer of the idea response-surface methodology can be defined as an empirical statistical technique employed for multiple regression analysis by using quantitative data obtained from properly designed experiments to solve multivariate equations simultaneously.

The graphical representations of these equations are called response surfaces, which can be used to describe the individual and cumulative effect of the test variables on the response and to determine the mutual interactions between the test variables and their subsequent effect on the response.

5.2 Techniques of the Response surface methodology

Basically RSM is a combination of statistical experimental design fundamentals, regression modelling techniques, and optimisation methods. Response Surface Methodology (RSM) uses the following Design of experiments (DOE) techniques:

- Box-Behnken Design (BBD)
- Central Composite Design (CCD)
- Full & Fractional Factorial Designs
- Regression analysis methods

DOE techniques are employed before, during, and after the regression analysis to evaluate the accuracy of the model.

5.3 Suitability of the RSM process

The main idea of RSM is to replace a complicated response function with an approximate function by studying the relative significance of the effects of several factors supposed to have influence on the response of interest. RSM can be viewed from three major standpoints:

1. If the system response is rather well discovered, RSM techniques are used to find the best (optimum) value of the response.
2. If discovering the best value is beyond the available resources of the experiment, then RSM techniques are used to at least gain a better understanding of the overall response system and can be used to identify new operating conditions that produce demonstrated improvement in product quality over the quality achieved by current conditions.
3. If obtaining the system response necessitates a very complicated analysis that requires hours of run-time and advanced computational resources then a simplified equivalent response surface may be obtained by a few numbers of runs to replace the complicated analysis.

5.4 Response Surface Methodology: An overview

Assume that the true response, y, of a system depends on k controllable input variables (or factors) X1, X2,X3 , ..., Xk. Then the relationship can be represented as:

$$y = f(X1, X2, X3,...,Xk) + e \text{ ----------- } [1]$$

The function f is called the true response function, form of which is unknown and usually complicated, and f is a term representing sources of variability not accounted for in f. The term e is treated as a statistical error. Usually, e includes effects such as measurement error on the response, background noise, the effect of other variables, and so on, and often assumed to have a normal distribution with mean zero. The variables X1, X2, ...,Xk in equation [1] are known as natural variables, because they are expressed in the natural units of measurement, such as degrees Celsius, pounds per square inch, etc. In most of the RSM experiment, the natural variables are transformed into dimensionless coded variables with mean zero and the standard deviation same as that of the natural variables. Usually coded variables are calculated using the following formulae:

$$x_{ij} = \frac{X_{ij} - [(\max X_{ij} + \min X_{ij})/2]}{[(\max X_{ij} - \min X_{ij})/2]} \quad \ldots\ldots\ldots\ldots\ldots [2]$$

Where Xij is the ith natural variable for the jth experimental run. For two factors, (ie, k = 2), a second-order polynomial approximation of the true response function in terms of the coded variables will be written as:

$$\hat{\eta} = E(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 \quad \ldots\ldots\ldots\ldots [3]$$

where, xi are called 'coded variables' and ß's are called regression co-efficients. The terms X1, X2 are main effects and the term X1.X2 is called interaction. Adding the interaction term introduces curvature into the response function. In most cases, the second-order model is adequate for well-behaved responses since it can take on a wide variety of functional forms, so it often works well as an approximation to the true response surface. Moreover the parameters in a second order model can be easily estimated using least square method. In general a second-order model can be written as:

$$\hat{\eta} = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i<} \sum_{j=1}^{k} \beta_{ij} x_i x_j \quad \ldots\ldots\ldots\ldots [4]$$

This empirical model is called a 'response surface model'. The surface represented by f (Xi, Xj) is called a response surface. The response can be represented graphically, either in the three-dimensional space or as contour plots that help visualise the shape of the response surface. Contours are curves of constant response drawn in the Xi, Xj plane keeping all other variables fixed. Each contour corresponds to a particular height of the response surface. A contour plot is formed by a series of horizontal & vertical lines. The horizontal axis plots the most important factor in the experiment and the vertical axis plots the second most important factor in the experiment.

5.5 Methodology of RSM

RSM follows a sequential approach and the methodology is based on four basic phases:

Phase 1

The first stage is a generic step for screening factors. The objective of factor screening is to reduce the list of candidate variables to a relatively few so that subsequent experiments will be more efficient and require fewer runs or tests. The screening is based on main effects estimation.

Phase 2

The object of phase 2 is to fit a second-order model for the factors identified from screening experiment. A correct choice of design will ensure that the response surface is fit in the most efficient manner. The choice of a suitable design depends on the number of factors under consideration and the coverage of the chosen design over the region of interest on the response surface. Most desirable features of a chosen design are orthogonality, i.e., main effects and block effects are estimable independently and rotatability, i.e., constant predictability at all points equidistant from the design centre. Based upon the desirable features, most preferred designs are Central Composite Design (CCD) and Box-Behnken Design (BB). CCD is appropriate for evaluating linear or quadratic response surface models and is often recommended for sequential experimentation. BB, on the other hand, can be used for performing non-sequential experiments. CCD usually has axial points outside the design periphery. Although these design points have significant contribution towards design accuracy, still they are not desired in many cases when these conditions are beyond the safe operating limits. BB design ensures that all factors are set within the experimental periphery, but has lower accuracy than CCD.

Phase 3

The objective of this phase is to identify the theoretical value of factor region that yields the optimal response. Some commonly used optimisation techniques are "Best corner", "Steepest ascent/descent" and "Optimal plot" techniques.

Among these techniques, "Optimal plot" technique provides the "best guess" as to where to run the experiment so as to obtain the desired optimal response.

Phase 4

Phase 4 begins when the process is near the optimum. The step-wise regression procedure is followed for adding or deleting model terms depending on probabilities (p-values). The final model can be build up from the simplest models by adding and testing higher-order terms (the "forward" direction), or the final model can be reached starting with the full second-order model and eliminating terms until the most parsimonious, adequate model is obtained (the "backward" direction). Once an appropriate approximating model has been obtained, this model may be analysed to determine the optimum conditions for the process. The final model should have minimum residuals or error of prediction.

5.6 Applications of RSM

1. The application of RSM is aimed at reducing the cost of expensive analysis methods and their associated huge investment of resources and volumes of numerical data analysis. This particular advantage has paved the way for its successful application in different disciplines such as chemical and pharmaceutical processes, biological/biochemical processes, food science, production engineering, air quality analysis and toxicological research and computational and simulation studies.
2. Researchers from different fields in recent years have published several interesting applications of response surface methodology.
3. C J Stevens (Jr) of NASA, United States, integrated RSM with computational fluid dynamics (CFD) for prediction of combined cycle propulsion components in hypersonic jet fighters.
4. Neda and co-workers of Memorial University of Newfoundland, Canada, combined Monte Carlo simulation method with the RSM to compute permanent displacement of submarine slope under earthquake loads. The results obtained from the experimental study were reported to be almost identical to that obtained from replicating the actual model.

5.7 Uses of RSM

1. To determine the factor levels that will simultaneously satisfy a set of desired specifications.
2. To determine the optimum combination of factors that yields a desired response and describes the response near the optimum.
3. To determine how a specific response is affected by changes in the level of the factors over the specified levels of interest.
4. To achieve a quantitative understanding of the system behaviour over the region tested.
5. To predict properties throughout the region-even at factor combinations not actually run.
6. To find conditions for process stability insensitive spot.

5.8 Limitations of the RSM technique

RSM suffer from some serious drawbacks which can be listed below:

One is its sequential approach. This sequential approach of RSM can be considered as a disadvantage when the experimental preparation is time-consuming or its duration is long. Cheng and his co-workers suggested to integrate factor screening and response surface development on the same experiment and proposed a new approach, which can serve as a link between the two.

Another limitation of RSM is sensitivity to system noise. It is assumed in RSM that the experimental noise factors controllable during process development for purposes of a designed experiment. This assumption reduces the robustness of the RSM models. Professor Taguchi modified RSM and developed a new approach known as robust parameter design methodology (RPD) that made RSM models insensitive (or robust) to changes in a set of uncontrollable factor.

REFERENCES

[1]. Aggarwal A., Singh H., Kumar P. & Singh M (2008), “Optimising power consumption for CNC turned parts using response surface methodology and Taguchi technique –A comparative analysis”, Journal of material processing technology, 200, pp. 373-384.

[2]. Aggarwal A., Singh H., Kumar P. & Singh M. (2008), “Optimization of multiple quality characteristics for CNC turning under cryogenic cutting environment using desirability function,” Journal of material processing technology, 205 pp. 42-50.

[3]. Groover, M.P.(1990), “Fundamentals of modern manufacturing-Materials processes and Systems”, Prentice-Hall, Englewood Cliffs, NJ.

[4]. Grzesik W., Nieslony P. (2004), "Prediction of friction and heat flow in machining incorporating thermo physical properties of the coating –chip interface," Wear, 256(2004) , pp. 108-117.
[5]. Gaitonde V.N., Karnik S.R &Davim J.P. (2008), "Selection of optimal MQL and cutting conditions for enhancimg machinability in turning of brass," Journal of materials processing Technology, 204,pp. 459-464.
[6]. Gandaris A., Lopez de Lacalle, L.N., Aizpitarte, X. & Lamikiz,A.(2008), "Study of the performance of the turning and drilling of austenitic stainless steels using two coolant techniques ," Int. J. Machining and Machinability of Marerials, Vol.3, Nos.1/2, pp.1-17.
[7]. Kennametal Inc.(1999), "Steel machining Catalogue 9008," Trade Catalogue, U.S.A.
[8]. Lin W.S., Lee B.Y.& Wu C.L(2001), "Modelling the surface roughness and cutting force for turning," Journal of Materialls Processing Technology, 108, pp.286-293.
[9]. Tetal K. (1989), "Machining of Stainless Steels Handbook, 9th ed., ASM International, pp. 681.
[10]. Tarng Y.S., Nian C.Y. & Yang W.H (1999), "Optimisation of turning operations with multiple performance characteristics", Journal of Materials Pocessing Technology, 95, pp. 90-96
[11]. Abhang L B, Hameedullah M 2010 Chip-tool interface temperature prediction model for turning process. Int. J. Eng. Sci. Technol. 2(4): 382–393.
[12]. Bouacha K, Yallese M A, Mabrouki T, Rigal J-F 2010, " Statistical analysis of surface roughness and cutting forces using response surface methodology in hard turning of AISI 52100 bearing steel with CBN tool". Int. J. Refractory Metals and Hard Materials 28: 349–361.
[13]. Ozel T, Hsu T K, Zeren E 2005, " Effects of cutting edge geometry, workpiece hardness, feed rate and cutting speed on surface roughness and forces in finish turning of hardened AISI H13 steel". Int. J. Adv. Manuf. Technol. 25: 262–269.
[14]. Strafford K N, Audy J 1997, " Indirect monitoring of machinability in carbon steels by measurement of cutting forces". J. Mater. Processing Technol. 67(1–3): 150–156.
[15]. Saglam H, Yaldiz S, Unsacar F (2007), "The effect of tool geometry and cutting speed on mail cutting force and tool tip temperature". Mater. Design., 28: 101- 111.
[16]. D. C. Montgomery, Design and analysis of experiments, Wiley, Singapore, 1991.
[17]. M. S. Chua, M. Rahman, Y. S. Wong, H. T. Loh, " Determination of optimal cutting conditions using design of experiments and optimization techniques." Int. J. Mach. Tools Manuf., 33 (1993) 2, 297–305.
[18]. Al-Ahmari, A.M.A., "Mathematical model for determining machining parameters in multipass turning operations with constraints." Int. J. Prod. Res., 2001, 39, 3367–3376.
[19]. Coudhury, I. and El-Baradie, M., "Machinability assessment of inconel 718 by factorial design of experiment coupled with response surface methodology." J. Mater. Proc. Tech., 1999, 95, 30–39.
[20]. CochranWG,CoxGM. Experimentaldesigns. Bombay,India:Asia Publishing House; 1959.
[21]. Hassan, G. A., & Suliman, S. M. A. (1990). "Experimental modeling and optimization of turning medium carbon steel." International Journal of Production Research, 28(6), 1057–1065.
[22]. I. A. Choudhury, M.A. El-Baradie, " Surface roughness prediction in the turning of high-strength steel by factorial design of experiments". J. Mater. Process. Tech . 67 (1997) 55–61.
[23]. Design-Expert Software, Version 8, User's Guide, Technical Manual, Stat-Ease Inc., Minneapolis, MN, 2000.
[24]. W.S. Lin, B.Y. Lee, C.L. Wu, " Modeling the surface roughness and cutting force for turning." J. Mater. Process. Technol. 108 (2001) 286–293.
[25]. Noordin, M.Y. et al. (2004), "Application of response surface methodology in describing the performance of coated carbide tools when turning AISI 1045 steel.'', J. Materials Processing Technology, Vol. 145, pp. 46-58.
[26]. Hill, W.J. and W.G. Hunter, 1966, " A review of response surface methodology": A literature survey. Technometrics, 8: 571-590.
[27]. K. Kadirgama and K.A. Abou-El-Hossein 2005, " Force Prediction Model for Milling 618 Stainless Steel Using Response Surface Methodology", American Journal of Applied Sciences 2 (8): 1222-1227.
[28]. Hicks, C.R., 1993, "Fundamental Concepts in the Design of Experiments", 4th Edn. Saunders College Publishing, Holt, Rinehart and Winston.
[29]. Jenn-Tsong Horng, Nun-Ming Liu, Ko-Ta Chiang, " Investigating the machinability evaluation of Hadfield steel in the hard turning with Al2O3/TiC mixed ceramic tool based on the response surface methodology" Journal of Materials Processing Technology, Volume 208, Issues 1-3, 21 November 2008, Pages 532-541.
[30]. M.Y Noordin, V.C Venkatesh, S Sharif, S Elting, A Abdullah, "Application of response surface methodology in describing the performance of coated carbide tools when turning AISI 1045 steel", Journal of Materials Processing Technology, Volume 145, Issue 1, 1 January 2004, Pages 46-58.