# Evaluation and Prioritization of Key Parameters for Optimization of HSM of Ti Alloys

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**Abstract-**The scope of high speed machining for hard materials has been increased due to explorations in the field of applications of these materials in today's technological world. The applications of these materials including Titanium alloys especially used for aerospace are rapidly increasing due to emergent needs of customers and shorter product life cycles. High speed machining (HSM) of Titanium alloys is a more complex phenomenon than that of conventional materials and machining processes. Process optimization for HSM of Titanium alloys can significantly reduce the cycle time of machining processes resulting in reduced lead times, better project management and increased profits. There are several parameters that need to be optimized for better and cost effective machining of Ti alloys. But before optimization the identification and prioritization of these parameters is obligatory. In this paper a methodology has been developed for identification and prioritization of these key parameters. Expert opinions are integrated with Analytical Hierarchical Process (AHP) to define the priority of these parameters. The prioritized matrices will then form the basis for further optimization of these key parameters to be used for HSM of Ti alloys.
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**Introduction**:

With the introduction of high performing CAD/CAM systems and CNC machines, high speed machining (HSM) has carved a dominant position among other rapid manufacturing techniques. Along with the benefits of increased productivity, high quality surface finishes of manufactured parts are generated by using HSM technology. Cutting forces in HSM are significantly reduced as compared with the forces while machining parts on conventional speeds [1]. Usually burr-free edges are achieved and almost stress free components are machined by using HSM. High speed machining can be used to machine thin-walled work pieces also [1]. Minimization of heat effects on machined parts is another significant benefit of using HSM machining for manufacturing of parts having applications of high fatigue. The phenomenon of heat dissipation during chip formation results in reduced thermal warping and significant tool life is increased. In many cases, cooling fluids are rarely used while machining on high speeds [2]. Mostly HSM is run without cutting fluid and it can help to reduce contribution to environmental pollution also [3]. Having so many advantages, HSM has been widely used in aircraft, aerospace, precision manufacturing, optics, automobile industry and household applications. The benefits from high speed machining for milling of aluminium alloys are being taken since more than a decade while high speed machining of difficult to cut materials like titanium and its alloys is still relatively new [1]. Owing to special characteristics of superior corrosion resistance, temperature resilience and good strength-to-weight ratio, Titanium alloys are being extensively used in Petroleum, Biomedical, Aerospace, Sports and Automotive industries [4]. However, the benefits associated with these materials are not being taken extensively due to the poor machinibility of these difficult to machine materials. The selection of appropriate and optimal machining conditions and parameters is extremely important for machining of such alloys. Most widely used Titanium alloy for aerospace applications is Ti-6Al-4V. Due to the poor machinability ofTi-6Al-4V the selection and prioritization of this machining condition is crucial [5].

Decision making is very important in manufacturing engineering like other areas of engineering. AHP being a renowned decision making tool is being applied in industry for decades. There are numerous cases in engineering where AHP was successfully applied as a decision making tool. Many practitioners, researchers and decision makers have used this technique in their relevant work. Some previous studies stated the applications of AHP as a tool to support supply chain and logistics management, selection of appropriate software for specific applications, manufacturing simulation and facility layout design [6]. C.Kaharaman et al. used Fuzzy AHP for supplier selection in agile manufacturing system [7]. H.I.Lee and W.C.Chen used Fuzzy AHP approach and balanced score card (BSC) approach for evaluation of the performance of IT applications in manufacturing industry in Taiwan [8]. Different layout configurations for reconfigurable manufacturing system were prioritized and best of theses were selected by using AHP by Abdi, M.R. [9]. AHP was also incorporated by E. Bernroider and S.Koch for ERP selection process in small and medium enterprises [10]. Ayag, Z. developed an approach for combining Fuzzy AHP with simulation for selection of CAD software [11]. They also developed AHP and FAHP integrated approach for the vendor selection problem and CMMs software evaluation by using AHP. Zakria et al.used AHP for criteria evaluation and prioritization is used successfully in key parameters selection for CAD/CAM software of SMEs [6]. Similar research was also conducted by R.Venkata Rao in selection of appropriate design for metal stamping layouts and AHP was used as decision making tool [12]. AHP has also been used by G. Kannan for selection of appropriate CAD/CAM system [13]. In this research, this decision making approach was tested as Multi-criteria decision making tool for manufacturing industries. Many researchers and practitioners have used this technique in strategic and functional decision making processes. There are also numerous applications of AHP for decision making in academia for personal evaluations and selection of appropriate candidate [14]. Zakria et al. also used AHP in selection of best simulation software for manufacturing system [15].

There are many applications of AHP in other engineering areas like evaluation, forecasting, decision making, priority and ranking, planning and development, allocation of resources and cost and benefit analysis [16].

AHP methodology is considered as one of the best promising technique for evaluation, prioritization and selection of alternatives for multi criteria decision making problems. There are many applications of AHP in literature but so far there are few (if any) specific studies for evaluation and prioritization of factors for HSM of Ti alloys.

This study covers the investigation of important factors for machining of Ti Alloys. Prioritization of these factors has been executed by integrating Area Expert Opinion and Analytical Hierarchical Process (AHP). Relevant literature for machining of Ti alloys has been reviewed; the important factors for HSM of Ti alloys are discussed and selected for further research. These key factors are then prioritized by using the proposed methodology and these prioritized factors are then optimized for HSM of Ti Alloy. Main objective of this research is to enhance the capacity of machines by optimization of key parameters for machining. However before optimization, the selection and prioritization of these factors is very important to model simple optimization models.

Initially these factors were extracted from surveyed literature and selected for conventional and high speed machining. These factors were then investigated in detail in brainstorming sessions with machining experts. Matrices were developed for selected key parameters after which these factors were compared pair wise by experts. These matrices were then integrated with Analytical Hierarchical Process (AHP) for further validation and conclusion. Table 1 describes the important factors used in literature.

Table 1. Important factors for Machining of Metals

| **Important Parameters in literature** | | | | | |
|---|---|---|---|---|---|
| **S#** | ***Tool Parameters*** | ***Work Piece Material*** | ***Coolant Type & Flow*** | ***Insert Type & Geometry*** | ***Machine Parameters*** |
| 1 | Geometry of Tool | Condition of the material | Coolant Flow Rate | Geometry of insert | Speed (RPM) |
| 2 | No of Flutes / Inserts | Hardness | MQL or Dry Machining | Material of Insert | Feed (FPM) |
| 3 | Diameter of Tool | Rolled Extruded, cast, Forged | Type of Coolant | Coating type | Depth of Cut |

**Methodology:**

Identification of key parameters for high speed machining of difficult to cut material is not an easy task. The key parameters affecting the machinability of Ti alloys have been identified after formal discussion with area experts and an extensive literature review. AHP was then used to prioritize the factors by using pair-wise comparison. Human nature dictates that anyone who is involved in the process and is being asked to judge pair-wise relative importance of one parameter over the other may make inconsistent decisions, being so close to the process. Therefore, area experts with more than 20 years of combined machining experience who have been involved in operational and strategic decision making in a modern and cutting edge manufacturing system were selected to make the judgments. A questionnaire was distributed in matrix form asking a simple question: "How much important is one indicator over the other using a scale of 0-9"? This scale of preference was designed by Thomas Satty and is placed as Table 2.

A secondary benefit of this study will be streamlining the process of investment in HSM. Because investments made without proper identification of key issues and respective priority can lead to wrong decisions and consequently result in loss of precious resources like man-hours, machine hours, raw material etc; therefore, relative comparisons of different alternatives of key indicators are very necessary. AHP methodology is proposed for prioritization of factors for this issue.

Table2. Scale of preferences proposed By Thomas Satty

| **Preference weights/ level of importance** | **Definitions** | **Explanation** |
|---|---|---|
| 1 | Equally preferred | Equal importance to the objective |
| 3 | Moderately preferred | Judgments slightly favour one activity over the other |
| 5 | Strongly preferred | Judgments strongly favour one activity over another |
| 7 | Very strongly preferred | An activity is strongly favoured over another |
| 9 | Extremely preferred | The evidence favouring one activity over another is of the highest degree possible of affirmation |
| 2,4,6,8 | Intermediate preferred | Used to represent compromise between the preferences listed above |
| Reciprocals | Reciprocals are used for inverse comparison | |

Table3. Key factors with their abbreviations

| **Sr. No** | **Criteria** | **Abbreviation** |
|---|---|---|
| 1 | Geometry of tool | GT |
| 2 | Dia. Of tool | DT |
| 3 | Condition of the material | CM |
| 4 | Type of machining | TM |
| 5 | Geometry of inserts | GI |
| 6 | Material of inserts | MI |
| 7 | Speed | S |
| 8 | Feed | F |
| 9 | Depth of cut | DOC |
| 10 | Coating type of insert | CTI |

**Key parameters for HSM:**

Out of the factors mentioned in Table 1following factors were further used for prioritization. Table 3 represents the important factors and their respective abbreviations.

**Prioritization of Factors Using AHP:**

After several brainstorming sessions with machining experts, a set of nine important factors was identified and keeping in view the core objective of this study, the need for further prioritization of these factors in order to avoid less effective factors was felt and an AHP decision model for prioritizing key factor for high speed machining was implemented to further validate the results. The requirement matrix for pair-wise comparison was generated and then scored by the machining experts. Then pair-wise comparison of all the factors was carried out by using scale values given in Table 2. Eigen values were computed and the steps are mentioned in Table 4 and Table 5.

Table4. Requirement matrix for factors

| | **GT** | **DT** | **CM** | **TM** | **GI** | **MI** | **S** | **F** | **DOC** | **CTI** |
|---|---|---|---|---|---|---|---|---|---|---|
| **GT** | 1 | 1 | 1/3 | 1/3 | 1/2 | 1/5 | 1/7 | 1/8 | 1/9 | 1/3 |
| **DT** | 1 | 1 | 1/3 | 1/3 | 1/3 | 1/5 | 1/9 | 1/8 | 1/7 | 1/3 |
| **CM** | 3 | 3 | 1 | 1/2 | 1/5 | 1/4 | 1/8 | 1/8 | 1/9 | 1/4 |
| **TM** | 3 | 3 | 2 | 1 | 1/5 | 1/6 | 1/7 | 1/8 | 1/9 | 1/3 |
| **GI** | 2 | 3 | 5 | 5 | 1 | 1/5 | 1/9 | 1/9 | 1/8 | 1/2 |
| **MI** | 5 | 5 | 4 | 6 | 5 | 1 | 1/8 | 1/9 | 1/7 | 1 |
| **S** | 7 | 9 | 8 | 7 | 9 | 8 | 1 | 1/3 | 1/4 | 8 |
| **F** | 8 | 8 | 8 | 9 | 9 | 9 | 3 | 1 | 1/7 | 8 |
| **DOC** | 9 | 7 | 9 | 8 | 8 | 7 | 4 | 7 | 1 | 5 |
| **CTI** | 3 | 3 | 4 | 3 | 2 | 1 | 1/8 | 1/8 | 1/5 | 1 |
| **SUM** | 42.00 | 43.00 | 41.44 | 39.72 | 34.26 | 26.24 | 8.88 | 9.18 | 2.34 | 24.75 |

Table 5. Eigen Value Matrix

| | GT | DT | CM | TM | GI | MI | S | F | DOC | CTI | SUM |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **GT** | 0.024 | 0.023 | 0.011 | 0.011 | 0.015 | 0.008 | 0.016 | 0.014 | 0.047 | 0.013 | 0.182 |
| **DT** | 0.024 | 0.023 | 0.011 | 0.011 | 0.013 | 0.008 | 0.013 | 0.014 | 0.061 | 0.013 | 0.190 |
| **CM** | 0.071 | 0.070 | 0.024 | 0.013 | 0.006 | 0.010 | 0.014 | 0.014 | 0.047 | 0.010 | 0.279 |
| **TM** | 0.071 | 0.070 | 0.048 | 0.025 | 0.006 | 0.006 | 0.016 | 0.014 | 0.047 | 0.013 | 0.317 |
| **GI** | 0.071 | 0.070 | 0.121 | 0.126 | 0.029 | 0.008 | 0.013 | 0.012 | 0.053 | 0.020 | 0.523 |
| **MI** | 0.119 | 0.116 | 0.097 | 0.151 | 0.146 | 0.038 | 0.014 | 0.012 | 0.061 | 0.040 | 0.795 |
| **S** | 0.214 | 0.209 | 0.193 | 0.176 | 0.263 | 0.305 | 0.113 | 0.036 | 0.107 | 0.323 | 1.939 |
| **F** | 0.190 | 0.186 | 0.193 | 0.227 | 0.263 | 0.343 | 0.338 | 0.109 | 0.061 | 0.323 | 2.233 |
| **DOC** | 0.167 | 0.163 | 0.217 | 0.201 | 0.234 | 0.267 | 0.450 | 0.763 | 0.427 | 0.202 | 3.091 |
| **CTI** | 0.071 | 0.070 | 0.097 | 0.076 | 0.058 | 0.038 | 0.014 | 0.014 | 0.085 | 0.040 | 0.563 |

The Eigen value matrix was computed and the sum is given in the 11th column of Table 5.

| | | | | |
|---|---|---|---|---|
| = | $\frac{1}{10}$ | 0.182 | = | 0.0182 |
| | | 0.190 | | 0.019 |
| | | 0.279 | | 0.0279 |
| | | 0.317 | | 0.0317 |
| | | 0.523 | | 0.0523 |
| | | 0.795 | | 0.0795 |
| | | 1.939 | | 0.1939 |
| | | 2.233 | | 02233 |
| | | 3.09 | | 0.0309 |
| | | 0.562 | | 0.0562 |

As there are ten factors, therefore, in the next step the row sum is multiplied with total number of indicators. The importance of factors as percentage values is given below, for example, Speed (S) as 19.4%, Feed (F) as 22.33% and Depth of cut (DOC) as 30.9%.

| | |
|---|---|
| **GT** | 1.82% |
| **DT** | 1.90% |
| **CM** | 2.79% |
| **TM** | 3.17% |
| **GI** | 5.23% |
| **MI** | 7.95% |
| **S** | 19.39% |
| **F** | 22.33% |
| **DOC** | 30.90% |
| **CTI** | 5.62% |
| | |

In order to test and validate the selection of important parameters, consistency ratio (CR) is computed. To calculate CR, the relative values are set for each requirement based on estimated Eigen values. Requirement matrix is multiplied with percentage values and results are computed to evaluate CR value.

$$\begin{pmatrix} 1 & 1 & 1/3 & 1/3 & 1/2 & 1/5 & 1/7 & 1/8 & 1/9 & 1/3 \\ 1 & 1 & 1/3 & 1/3 & 1/3 & 1/5 & 1/9 & 1/8 & 1/7 & 1/3 \\ 3 & 3 & 1 & 1/2 & 1/5 & 1/4 & 1/8 & 1/8 & 1/9 & 1/4 \\ 3 & 3 & 2 & 1 & 1/5 & 1/6 & 1/7 & 1/8 & 1/9 & 1/3 \\ 2 & 3 & 5 & 5 & 1 & 1/5 & 1/9 & 1/9 & 1/8 & 1/2 \\ 5 & 5 & 4 & 6 & 5 & 1 & 1/8 & 1/9 & 1/7 & 1 \\ 7 & 9 & 8 & 7 & 9 & 8 & 1 & 1/3 & 1/4 & 8 \\ 8 & 8 & 8 & 9 & 9 & 9 & 3 & 1 & 1/7 & 8 \\ 9 & 7 & 9 & 8 & 8 & 7 & 4 & 7 & 1 & 5 \\ 3 & 3 & 4 & 3 & 2 & 1 & 1/8 & 1/8 & 1/5 & 1 \end{pmatrix} = \begin{pmatrix} 0.018 \\ 0.019 \\ 0.0279 \\ 0.0317 \\ 0.0523 \\ 0.0795 \\ 0.1939 \\ 0.2233 \\ 0.0309 \\ 0.0562 \end{pmatrix}$$

$$\begin{pmatrix} 0.183 \\ 0.175 \\ 0.255 \\ 0.301 \\ 0.502 \\ 0.938 \\ 2.576 \\ 3.251 \\ 4.427 \\ 0.617 \end{pmatrix}$$

For each matrix, Eigen values are computed and dividing it with averaged values obtained in the last step.

$$\begin{pmatrix} 0.183/.0182 \\ 0.175/.019 \\ 0.255/.0279 \\ 0.301/.0317 \\ 0.502/.0523 \\ 0.938/.0795 \\ 2.576/.1939 \\ 3.251/.2233 \\ 4.427/.309 \\ 0.617/0.526 \end{pmatrix} \begin{pmatrix} = \\ \\ \\ \\ \\ \\ \\ \\ \\ \lambda_{\max} \end{pmatrix} \quad \begin{matrix} 11.76666 \\ 11.29838 \\ 10.25872 \\ 10.45707 \\ 10.25393 \\ 12.3043 \\ 13.64303 \\ 14.73821 \\ 15.22686 \\ 11.96708 \end{matrix}$$

=11.76+11.30+10.26+10.45+10.25+12.30+13.64+14.73+15.11.96/10

$\lambda_{\max}$ =12.19

For computing consistency index.

$$CI = \frac{(\lambda_{\max} - n)}{(n-1)}$$

CI= (12.19-10)/(10-1)

CI=0.24

Random index (RI) values are required to calculate CR value also. Satty proposed RI table shown in Table 6. Selection of RI values is based on number of alternates and in current specific cases there are ten important parameters being used as alternatives and RI value for this case will be 1.51.

Table 6. Random index table

| **No of requirements** | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|
| **RI value** | 0.0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.51 |

$$CR = \frac{CI}{RI}$$

So

CR=0.24/1.51

CR= 0.16

As a general rule, Thomas Satty proposed that the consistency ratio of 0.10~0.20 is acceptable

[14]. For the current case the consistency ratio is 0.16 indicating that the judgments made by specialists are consistent and not biased. Further it also validates that the achieved results are acceptable and are less than ideal.

From the experts' point of view the Depth of cut (DOC), Feed (F) and Speed(S) are the important factors to be optimized to improve machining cycle time while geometry and diameter of tool play a lesser role.

Expert Choice (EC) software package is used to validate the results and test for consistency ratio again. Prioritization of factors based on the expert's opinion for this specific case is presented in Figure 1 and Figure 2.

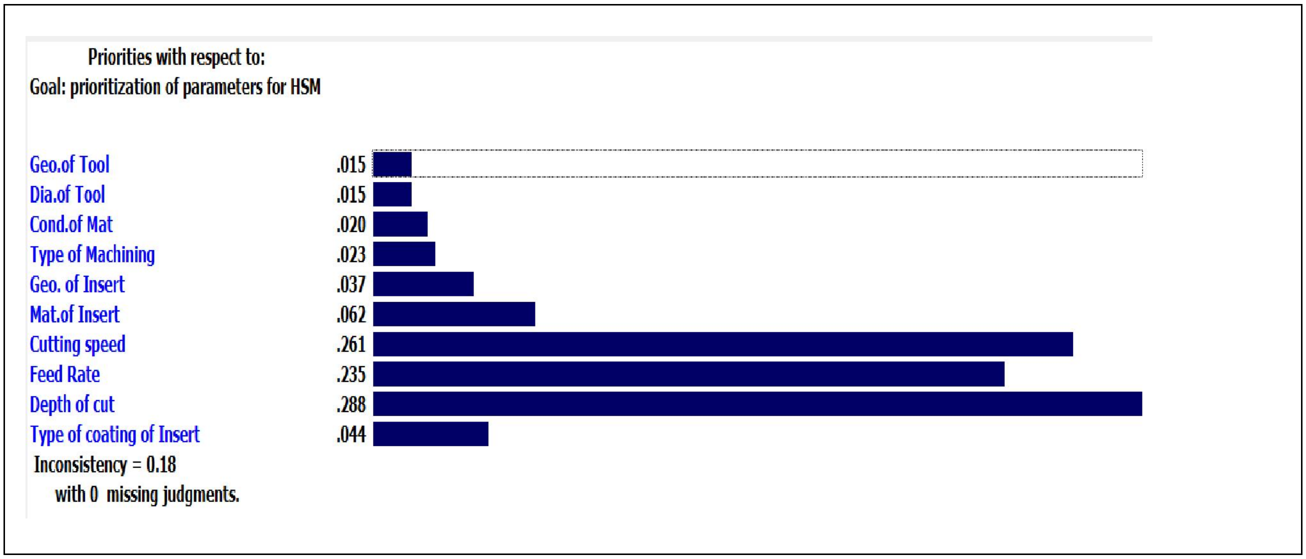


Figure 1. Prioritized factors by expert Choice

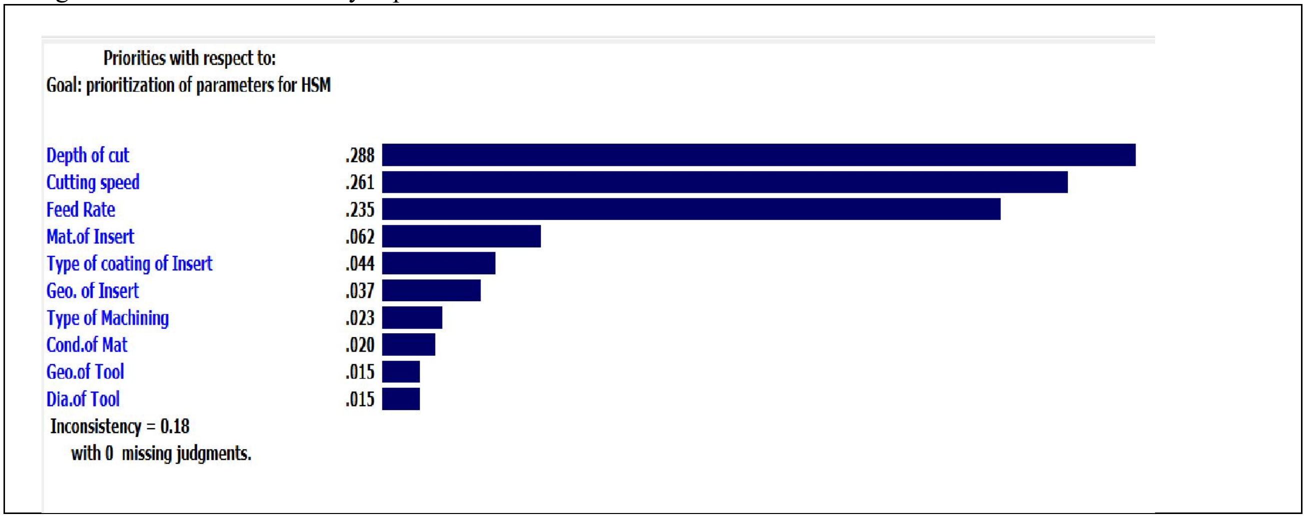


Figure 2. Prioritized factors by expert Choice

**Conclusion:**

AHP methodology represents a good solution in the development of decision support system to select important parameters for HSM of Ti Alloys. Therefore, this technique was used to make a logical decision for finalization of suggested parameters regarding HSM. In this study, AHP has been implemented to prioritize the important factors for HSM of Ti Alloys in aerospace industry. When we integrated experts' opinion with AHP, results showed that the depth of cut is the most important factor having maximum rating. The second and third factors were cutting speed and feed rate respectively. These three factors significantly contribute to the forces, frictions and temperatures during high speed machining of Ti Alloys while the least important factors like dia. of tool do not make any difference as the cutting speed remains constant.

In order to avoid errors of interpretation in calculation the process was repeated by using Expert Choice. The results obtained from both methods were consistent. The inconsistency by excel spread sheet was 0.16 and from expert choice it was 0.18, however both the values of consistency ratio are within acceptable limits.

These factors were further investigated to define a three level variable set of parameters through Design of Expert. The resultant set of parameters was then used for optimization of HSM for manufacturing of aerospace metal parts. The methodology for HSM process optimization consists of standard steps including running simulations, data analysis of simulation results and validation of simulated data through real time data acquisition during the machining process.

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8/2/2013