VOL. 11, NO. 22, NOVEMBER 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

STUDY OF TOOL LIFE OF UNCOATED WC-Co INSERT DURING FLAME ASSISTED MACHINING OF 316L STAINLESS STEEL

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ABSTRACT

This study presents an investigation for the development of tool life models during heat assisted machining and conventional dry end milling of AISI 316L stainless steel. The models have been developed and compared in order to evaluate the influence of external heat in machinability improvement of AISI 316L stainless steel using uncoated WC-Co insert. Three (3) level factorial design was utilized in establishing the tool life models in terms of cutting speed and feed as independent cutting parameters. All of the machining tests have been conducted within particular range of parameters using 100% cutter immersion. Tool life and response contours of metal removal have been investigated. Analysis of variance (ANOVA) was used to determine the most significant factors affecting the tool life. The results show that cutting speed is the main influencing factor on the tool life of uncoated WC-Co insert during cutting at both elevated temperature condition or while conventional machining at room temperature of AISI 316L stainless steel. This is followed by the feed and the machining temperature in the same order.

Keywords: 316L stainless steel, heat assisted machining, uncoated WC-co insert, tool life.

INTRODUCTION

Over the years, conventional machining of difficult to cut materials has proven to be costly in terms of regular tool wearing and consequent shorter tool life. This has been a reason for many researchers to evolve with realistic and low cost technique for machining materials like AISI 316L and other duplex type stainless steel as studied by Ranganathan *et al.* (2010) and Dolinsek (2003). Various research studies have reported poor machinability of various forms of stainless steels due to their low densities and thermal conductivities (Nomani *et al*., 2013; Mahdavinejad and Saeedy 2011). These poor machinability characteristics of stainless steel play a key role in determining the life of cutting tools. Several machining procedures and techniques were worked-out, which essentially aimed in improving the life of cutting tools. This includes deploying cryogenic treatment as a means to prolong the cutting time of tools. Gill *et al*. (2011) subjected an uncoated WC-Co insert to cryogenic treatment at two different level of temperature (-1100C: shallow treatment and -1960C: deep treatment). Their results revealed superior performance and prolong tool life of cryogenically treated uncoated WC-Co inserts compared to non-treated ones. Use of alternative cutting fluids like palm oil and vegetable oil based was proposed at many instances by Sharif *et al*. (2008) and Weinert *et al*. (2004). Other techniques were found in Ciftci, (2006) and Bonnet *et al*. (2008) which deployed the use of coated tools in order to reduce tool wear and improve tool life.

However, softening the workpiece material rather than strengthening the cutting tools have been reported to prolong tool life during metal cutting. Ginta *et al.* (2009) employed a heat assisted machining technique to improve the performance and prolong the tool life of uncoated WC-Co end mill inserts. The results revealed that workpiece preheating significantly improves tool life and performance of uncoated WC-Co inserts during machining titanium alloy Ti-6Al-4V. In that work, they did not establish the relationship of primary machining variables and their resulting influence on tool life of uncoated WC-Co insert. Such machining relationship was presented in various researches (Ginta *et al.,* 2007; Noordin *et al.,* 2004) in order to establish an adequate functional relationship between the response (tool life) and the machining parameters such as cutting speed, feed and depth of cut using a collection of mathematical and statistical technique based on response surface methodology (RSM).

The RSM is extensively utilized for modelling machining relationship between the input parameters and the output responses. Ginta *et al.* (2007) employed a small central composite design CCD to develop a tool life model for uncoated WC-Co insert while dry end milling titanium alloy Ti-6Al-4V. From their tool life model, it was revealed that cutting speed, feed and axial depth of cut significantly affected the tool life of uncoated WC-Co insert in the same order. An increase of these cutting variables was reported to results in reduction of the life of the tool. Saedon *et al*. (2012) established first and second order tool life models while cutting hardened tool steel AISI D2. The models were established in terms of cutting speed, feed per tooth and depth of cut, using response surface methodology. Their tool life equation reveals that cutting speed is the primary influencing factor on the tool life, accompanied by feed per tooth and depth of cut.

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The RSM is ideal for establishing, improving and optimizing the procedure which usually gives an over-all viewpoint of the system response within the design space, as exemplified by Montgomery (2008). Even so, optimum machining parametric condition while heat assisted machining of AISI 316L stainless steel using uncoated WC-Co insert is evidently lacking in the widely published literatures. Emphasis on optimization of cutting parameters is significant in terms of cost, time and quality of the machining products. In addition, determination of the best machining parameters will significantly improve the cutting efficiency during heat assisted machining of AISI 316L stainless steel. Hence, the goal of this study is to establish a mathematical relationships of the machining parameters affecting the tool life of uncoated WC-Co insert during end milling AISI 316L stainless steel using heat assisted machining and while machining at room temperature condition. Furthermore, the investigation will unveil most significant factors affecting the tool life of uncoated WC-Co insert and determine optimum machining parameters for cutting AISI 316L stainless steel using both heat assisted machining and dry machining condition**.**

RESPONSE SURFACE METHODOLOGY

RSM is a collection of mathematical and statistical techniques that are useful for the modelling and analysis of problems in which a response of interest is influenced by several variables with the objective to optimize the response (Montgomery, 2008). RSM models are widely developed in order to capture specific parameter and their influence on the machinability factors. Temperature field, tool life, cutting forces and surface roughness on the machined surfaces have been the widely investigated factors during heat assisted machining of difficult to cut materials. The first step in RSM is to find a suitable approximation for the true functional relationship between 'y' and the set of independent variables. A low order polynomial is usually employed at some region of the independent variables. Where the response is found befitting by a linear function of the independent variables, the approximating function will be a first order model (Montgomery, 2008), as follows,

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k + e \quad (1)$$

However, should there be a curvature in the system; a polynomial of higher degree given in Equation 2, should be used. This is called a second order model.

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<} \sum_{j} \beta_{ij} x_i x_j + e \quad (2)$$

Most often, all RSM problems use either one or the combination of both of these models. In either model, the levels of each factor are independent of the levels of other factors. In order to obtain an effective result in the approximation of polynomials the proper experimental design must be used to collect data. Once the data are collected, the Method of Least Square is used to estimate the parameters in the polynomials. The response surface analysis is performed by using the fitted surface. Further details about the response surface models are available in (Kurniawan *et al.,* 2010; Patwari *et al.,* 2009).

EXPERIMENTAL DESIGN AND METHODOLOGY

The machining experiments were conducted on Excel FU 281 universal milling machine with main drive spindle speed in the range of 40 – 2000 rpm. It has table work surface of 300 x 1250mm. The table can swivel to left and right of 45inch. The table moves longitudinally traverse: 845mm, crosswise traverse: 230mm and vertically traverse: 390mm. The RSM technique was also used to design the machining tests conducted both at room temperature and at elevated temperatures, in order to achieve valid and reliable conclusions in an effective and economical manner. Workpiece composition of 316L stainless steel is given in Table-1.

Table-1. Composition of 316L austenitic stainless steel.

C	Mn	Si	P	S	Cr	Mo	Ni	N	Fe
0.03	2.0	0.75	0.04	0.03	18.6	3.2	10.0	0.1	Bal.

Notably, the choice of both selected cutting speed and feed shown in Table-2 conforms within the machine's range.

Table-2. Independent machining variables and condition for this study.

S/no	Parameters	Levels		
		Low	Center	High
1	Coding Number	-1	0	+1
2	Cutting Speed (m/min)	50	79	100
3	Feed (mm/tooth)	0.15	0.25	0.4
4	Axial Depth of Cut (mm)	1		
5	Radial Depth of Cut (mm)	40 (Full cutter immersion)		
6	Cooling Fluid	None		
7	Focus Height (mm)	7.5		
8	Lead Distance (mm)	40		

A total of 13 different machining tests have been conducted each, at room temperature and at elevated temperatures respectively. These 13 tests consist of 8 corner points located at the vertices of the cube and a centre point repeated 5 times. Experiments were conducted in random order as presented in the RSM matrix. The machining was performed with 40mm diameter end mill cutter fitted with one uncoated triangular shaped uncoated WC-Co insert. Tool life was recorded with Mitutoyo quick vision pro QVE 202, every 120mm of cutting distance. The QVE 202 offers 0.1µm resolutions on staged glass size of 269 x 311mm. It has a maximum stage loading of 195kg that moves 250mm, 200mm and 200mm along X, Y and Z axis respectively. The relationship between the response of interest (tool life) and process parameters were represented. All the machining tests were carried out on the same machine tool, with the same batch of cutting insert using the same machining variables as shown in Table-2.

RESULTS AND DISCUSSION

Experimental results of tool life at varying combinations of cutting speed and feed are shown in case of TEM and conventional machining at room temperature.

Table-3. Tool life result for TEM and conventional machining (CM).

S/n	Cutting Speed	Feed	TEM	CM
1	50	0.25	9.4	5.8
2	79	0.25	17.5	11.3
3	79	0.25	17.7	11.6
4	79	0.25	15.8	10.1
5	100	0.4	9.7	5.24
6	100	0.15	12.1	8.13
7	79	0.25	17.7	11.5
8	50	0.15	13	7.4
9	100	0.25	11.7	6.7
10	79	0.25	17.6	11.7
11	79	0.4	11.7	7.4
12	50	0.4	7.5	5.2
13	79	0.15	17.7	11.7

With adopted 0.3mm average flank wear criterion, maximum value of tool life was obtained after 17.50 minutes of cutting time at feed *f* of 0.25 mm/tooth, cutting speed *V* of 79m/min and axial depth of cut (DOC) of 1mm, during heat assisted machining. Tool life was contrarily obtained at the same machining condition after 17.70 minutes while conventional machining at room temperature. Evidently, elevating the temperature of the material in addition to moderate feed and cutting speed, lead to increase of the cutting time of uncoated WC-Co insert during end milling AISI 316L stainless steel. The RSM model reveals mathematical relationship of the machining parameters which conforms to experimental observation.

RSM ANALYSIS

The experimental results were statistically evaluated by using analysis of variance (ANOVA), which has been effectively used for assessing the factors that significantly influences the response of interest (tool life). The input variables for the room temperature machining condition are the cutting speed, feed and axial depth of cut. The coded values of the design matrix presented earlier in Table-3 were used for the transformation given in Equation 3, below.

$$x_1 = \frac{\ln V - \ln 79}{\ln 100 - \ln 79}, \quad x_2 = \frac{\ln f - \ln 0.25}{\ln 0.4 - \ln 0.25}, \quad x_3 = \frac{\ln d - \ln 1}{\ln 1 - \ln 1} \quad (3)$$

The impact of the model terms was assessed by examining the sequential sum of squares with particular interest on the *prob.>F* column. This column depicts the significance of the model fitness. A 95% confidence level was adopted for the analysis, where model type with *p-value (Prob.>F)* of less than 0.05 were considered significant. Consequently, this study selected a significant model type for analysis. Where more than one model types are selected, the highest order model may be adopted.

TOOL LIFE MODEL DURING CONVENTIONAL AT ROOM TEMPERATURE

The Fit Summary results revealed that the quadratic model was statistically significant for tool life response during conventional end milling AISI 316L stainless steel. Consequently, the quadratic model was chosen for analysis. The quadratic model obtained for the tool life during conventional end milling AISI 316L stainless steel using uncoated WC – Co insert at room temperature is given in Equation 4 as obtained in terms of coded terms as follows;

$$T_{CM} = -27.51 + 1.02V + 9.62f - 6.58E03V^2 - 29.51f^2 - 0.077Vf \quad (4)$$

As revealed in the fit summary table of tool life during conventional machining, quadratic models were found significant, acquiring *p-value* < 0.05 *(Prob.>F)*. The ANOVA is shown in Table 4 for the tool life model during conventional machining at room temperature which depict the *p-value (prob.>F)* as 0.0005. Far obviously lower than the significant level of 0.05. This substantiate the validity of the model. The lack of fit F-value of 0.1742 during conventional dry machining indicated that the lack of fit was not significant relative to pure error. The model equation is presented with factors *V* and *f* which represents cutting speed and feed respectively. These are the only model terms investigated in this study. These model terms solely predict the tool life of uncoated WC - Co insert during conventional end milling of 316L stainless steel. Additionally, the ANOVA table during the conventional machining at room temperature depicts the F-value of the cutting speed *V* as 58.17, emerging higher than that of the feed *f* as 0.18. This means that cutting speed is far significant in determining the tool life of uncoated WC - Co insert during conventional end milling 316L stainless steel.

Table-4. ANOVA for tool life model of uncoated WC-Co Insert at room temperature condition during end milling AISI 316L stainless steel.

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	77.99	5	15.60	20.67	0.0005	Significant
A	43.90	1	43.90	58.17	0.0001	
B	0.14	1	0.14	0.18	0.6816	
A²	43.92	1	43.92	58.20	0.0001	
B²	0.53	1	0.53	0.70	0.4291	
AB	0.24	1	0.24	0.32	0.5911	
Residual	5.28	7	0.75			
Lack of Fit	3.57	3	1.19	2.78	0.1742	Not significant
Pure Error	1.71	4	0.43			
Cor Total	83.27	12				

TOOL LIFE MODEL DURING HEAT ASSISTED MACHINING

Additionally, the tool life model during heat assisted machining is shown in Equation 5.

$$T_{TEM} = -29.92 + 1.29V - 2.84f - 8.817E-003V^2 \quad (5)$$

The model's coefficient is presented in terms of coded terms as cutting speed *V* and feed *f*. A quadratic model was equally found befitting the tool life during heat assisted machining of AISI 316L stainless steel using uncoated WC - Co inserts. The ANOVA is shown in Table-5 for the tool life model during heat assisted machining depicting the *p-value (prob.>F)* as 0.0004. Hence, the validity of the model is established with this fact. The lack of fit F-value of 0.1152 during heat assisted machining justified that the lack of fit was not significant relative to pure error. In comparison to the model obtained in Equation 4, the model terms are represented as cutting speed *V* with F-value 47.67, leading the feed *f*, as 8.12.

Table-5. ANOVA for tool life model of uncoated WC-Co insert during heat assisted machining AISI 316L stainless steel.

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	155.61	5	31.12	21.04	0.0004	Significant
A	70.50	1	70.50	47.67	0.0002	
B	0.012	1	0.012	8.12	0.9307	
A^2	78.71	1	78.71	53.22	0.0002	
B^2	1.97	1	1.97	1.33	0.2862	
AB	1.66	1	1.66	1.12	0.3247	
Residual	10.35	7	1.48			
Lack of Fit	7.66	3	2.55	3.79	0.1152	Not significant
Pure Error	2.69	4	0.67			
Cor Total	165.96	12				

This demonstrated that tool life of uncoated WC - Co insert during heat assisted end milling AISI 316L stainless steel is equally influenced largely by cutting speed than feed. Even so, high value of lack of fit *F-value* of 3.79 and *Prob.>F* of 0.1152 was revealed during heat assisted machining. Evidently, the lack of fit was not significant in accordance with pure error. The model terms during heat assisted machining included factor *V* and *f* representing cutting speed and feed respectively. These model terms dominantly dictated the tool life of uncoated WC - Co insert during heat assisted machining of 316L stainless steel.

MODEL ADEQUACY CHECK

The diagnostic plot of the residuals for tool life of uncoated WC-Co insert during conventional machining is shown in Figure-1. The plot reveals that the residuals generally fall on a straight line implying that the errors are distributed normally.

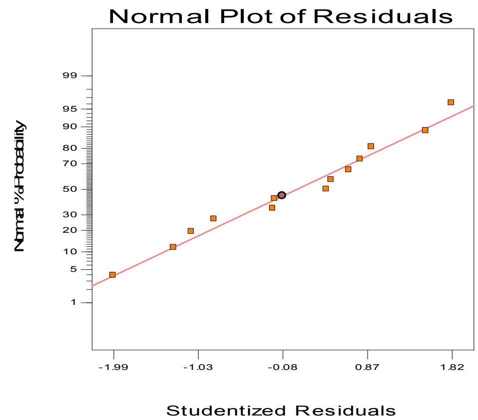

Figure-1. Normal probability plot of residuals of a tool life model for uncoated WC – Co inserts while end milling 316L stainless steel during conventional machining at room temperature condition.

In addition, the plot reveals that there is no obvious pattern and unusual structure to indicate any nonnormality or possibility to suspect any outlier. This meant that the model which is proposed in Equation 4 is adequate and there is no reason to suspect any violation of the independence or constant variance assumption (Noordin, 2003). The perturbation plot also indicates that an increase in both cutting speed and feed leads to decrease of tool life of uncoated WC-Co insert while conventional machining of AISI 316L stainless steel.

Following similar pattern, the diagnostic plot of the residuals for tool life during heat assisted machining is presented in Figure-2. The plot shows similar pattern of residuals clustering around the straight line, meaning that the errors are dispersed normally. Similarly, the plot revealed no obvious pattern and unusual structure to any nonnormality or possibility to suspect an outlier. This implies that the model proposed is adequate and there is no reason to suspect any violation of the independence or consistent variance assumption. The ANOVA table proved that cutting speed had been considerably dominant in determining the tool life of uncoated WC - Co insert during heat assisted machining. Even so, both feed and preheat temperature do equally affect the tool life of uncoated WC – Co end mill insert. From both the model equation and the perturbation plot, this assumption has been evidently validated.

3D linear response surface profiles are shown for the fitted quadratic models in Figure-3 and 4. The contour surfaces of the Equation 3 and 4, have notably shown that tool life becomes shorter with increasing cutting speed and feed rate. However, during heat assisted machining, preheat temperature have evident impact on the tool life of uncoated WC-Co insert.

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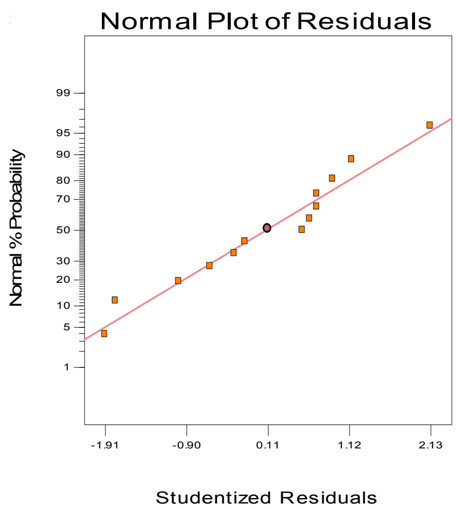

Figure-2. Condition when wheel zigzag gets over block.

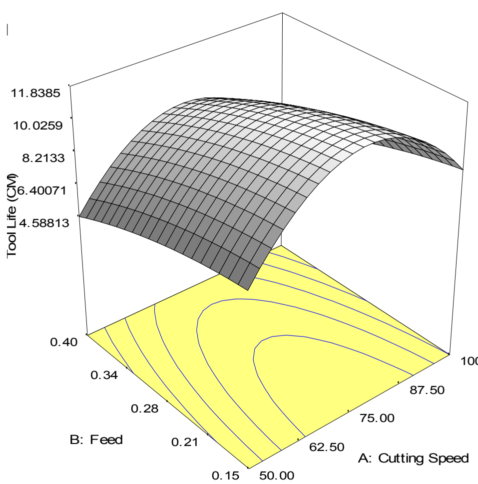

Figure-3. Response surface plot of a tool life model of uncoated WC- co insert during conventional end milling of 316L stainless steel at room temperature condition.

Equation 3 and 4 was found valid for end milling of 316L stainless tool steel using uncoated WC – Co inserts within the conditions below:

50m/min ≤ Cutting Speed ≤ 100m/min

0.15mm/min ≤ Feed per Tooth ≤ 0.4mm/min

Depth of cut of 1mm

It should be noted that both cutting speed and feed per tooth had been a significant factor in determining tool life of uncoated WC – Co Insert during end milling of AISI 316L stainless steel at either machining condition.

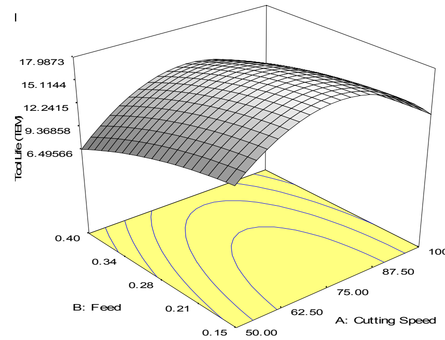

Figure-4. Response surface plot of a tool life model of uncoated WC- Co insert during heat assisted machining of 316L stainless steel.

The influences of cutting speed and feed rate on the overall tool life of uncoated WC - Co insert are examined in Figure-5 and Figure-6. It is notable that the tool life decreases with increase of cutting speed during either heat assisted machining or conventional machining at room temperature condition.

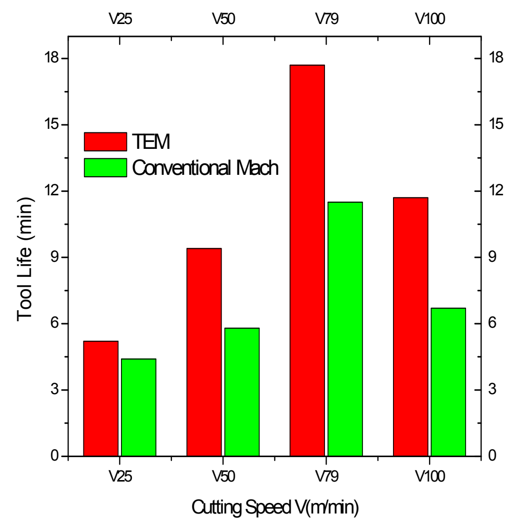

Figure-5. Comparative influence of cutting speed on tool life of uncoated WC-Co insert during end milling 316L stainless steel while TEM and conventional.

Machining at room temperature

However, the tool life decreases when the feed per tooth is increased especially with a combination of lower cutting speed. The tool life curve against cutting speed have evidently indicated an obvious decrease of tool life at cutting speed *V* of 100 m/min which invariably relates to the feed *f* of 0.25mm/tooth with an aggressive average flank wear observed during this experimental condition. Notably, tool life has shown a decreasing trend at this condition. These observations have therefore necessitated the need to arrive at optimal machining condition for which AISI 316L stainless steel will be cut with appreciable and longer tool life.

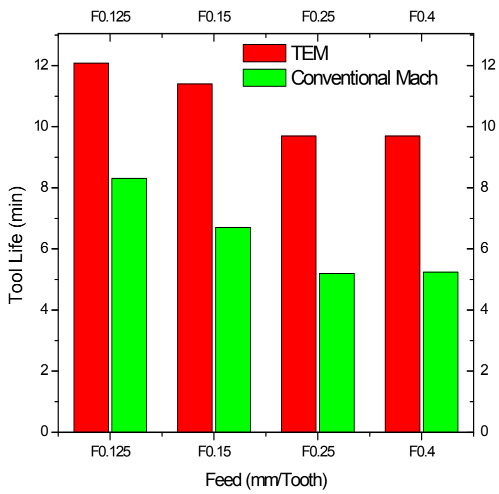

Figure-6. Comparative influence of feed on tool life of uncoated WC-Co insert during end milling 316L Stainless steel while TEM and conventional machining at room temperature.

NUMERICAL OPTIMIZATION FOR TOOL LIFE DURING END MILLING 316L STAINLESS STEEL

It was the objective of this study to identify an acceptable machining condition in which tool life may be extended. Tool life, was set to a maximum desirability goal using the optimization package of design expert suite. Tool life of uncoated WC-Co end mill insert was set on the need to be useful beyond 17 minutes of cutting time in order to save cost in terms regular tool change and machining time. The purpose of including preheat temperature is to suitably overcome the strength of the substrate at the intended machined region by using end mill cutter. The input parameters: preheat temperature (during heat assisted machining), cutting speed and feed are set in given ranges between upper and lower levels (i.e. V= 50 – 100m/min and f= 0.15 – 0.4mm/tooth). This means that it may be desired to have a tool life beyond 17 minutes within the ranges of the parameters investigated.

Table-6. Possible optimal solution for end milling 316L stainless steel with uncoated WC – Co insert during heat assisted machining and while conventional machining at room temperature condition.

Processes	Optimized Conditions	Machining	Optimize Response		Desirability
	V (m/min)	f (mm/tooth)	Preheat Temp (^{0}C)	Tool Life (min)	
CM	79.00	0.15	-	11.8	1
TEM	79.00	0.15	418	17.9	1

The result of possible optimal solutions during heat assisted machining with oxyacetylene flame and while conventional machining at room temperature conditions within the range of parameters earlier presented is given in Table-6 using an optimization method developed by Derringer and Suich. The closer the desirability value is to 1, the better is the response optimization.

CONCLUSIONS

Two empirical models have been obtained for tool life of uncoated WC – Co insert during conventional machining and heat assisted machining of AISI 316L Stainless steel. At both room temperature and elevated machining condition, cutting speed have shown a dominant influence in determining tool life of uncoated WC-Co insert than feed. The optimal machining condition for end milling AISI 316L stainless steel with uncoated WC – Co Insert during heat assisted machining and while conventional machining at room temperature condition was found to be at cutting speed V, 79 m/min and feed f, 0.25mm/tooth. Notably, the tool life was found to be higher during heat assisted machining at temperature H, of 418^{0}C. Influence of external heat source during heat assisted machining have substantially proven to increase the cutting time of uncoated WC - Co insert during machining AISI 316L stainless steel from 11.3 minutes to 17.5 minutes with evident decrease of average flank wear and machine vibration.

ACKNOWLEDGEMENTS

The authors humbly acknowledged the sponsorship received from the Centre for Graduate Studies of the Universiti Teknologi Petronas – Malaysia, and Bio – Medical Technology MOR, under Fundamental research grant scheme (FRGS) cost center: 0153AB – K31

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