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STUDY ON THE MACHINABILITY OF 316L STAINLESS STEEL USING FLAME ASSISTED MACHINING

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ABSTRACT

Flame assisted machining is a promising machining process targeted at improving the machinability of difficult to cut materials. Oxyacetylene flame as a heating mechanism is dominantly applied in heat assisted machining with single point turning tools. Investigations with end milling cutters which have a wider cutting area were not explored. Even so, with this approach, previous investigations have notably predisposed interest on machinability end result. As a result, varying machinability improvements have been reported by adopting same approach. However, investigation of the heat source parameters and their influence on the machinability factors were not reported in the wide published literatures. In this work, mathematical model of the flame spot diameter as heat source factor responsible for influencing machinability outcome was obtained. An optimal spot diameter was developed to reconcile the heat source from oxyacetylene flame for application with 40mm diameter end mill tool holder fitted with honed edge insert. Heat source parameters namely focus height, oxygen pressure, acetylene pressure and resident time (FOAR) are investigated as the independent variables responsible for varying spot diameter utilizing Analysis of variance (ANOVA). A response surface methodology was used for the design and finding the optimum flame spot size which will yield minimum heat affected area and superior machinability improvement. The established empirical model suggested that flame spot diameter is influenced by focus height, oxygen gas pressure, acetylene gas pressure and resident time in the same order. It was found that catastrophic wear transpired towards the end of the tool life criterion for several test conditions during dry machining at room temperature. Flame assisted machining was evidently discovered to increase the tool life of uncoated WC – CO end mill insert. With flame assisted machining, surface finish has increased by 80 % when the cutting speed was purposely changed from 79 to 125 m/min.

Keywords: flame assisted machining, spot diameter, and oxyacetylene flame.

INTRODUCTION

Concerted efforts have been made to portray the feasibility of using heat assisted machining through using various heating mechanism like laser beams, plasma heat, and electrical source heating among others. As mentioned in Skaverina and Shin [1], 15% reduction in cutting force and feed force over a conventional process while using laser beam as heat source when machining compacted graphite iron. Leshock et al [2] used plasma heat when machining Inconel 718. Their study observed 30% and 40% improvement of surface finish and tool life respectively. Ginta et al [3] reported 71% tool wear reduction during heat assisted machining using induction heating method. Control of the heat source factors like spot diameter, scanning speed and temperature distribution is the major challenge affecting the heat assisted machining processes. This predicament worth more consideration when using combustion flame like oxyacetylene flame for local heating. Even so, very few investigations are available which uses oxyacetylene flame as a heat source during heat assisted machining process. The application of flame heating as mechanism for heat source like oxyacetylene flame are generally very unpopular as a result of difficulties in focusing the flame for local heating, inspite of its low cost in addition to satiable heat penetration to width potentials. Davami and Zadshakoyan [4] utilized oxyacetylene flame during heat assisted machining to cut AISI 1060 steel on center lathe. As part of their investigation, they discovered reduction in tool wear and superior surface finish. Nonetheless, this particular study have not sought to examine the heat source factors in an effort to enhance the application of oxyacetylene with regard to local heating during the course of heat assisted machining process. Mukherjee and Basu [5] employed oxyacetylene flame as a heat source mechanism for cutting nickel chromium steel. Their own investigation revealed substantial machinability improvement with regards to tool life and surface finish. However, by concentrating on the machinability factors, the study neglected essential information on the mechanism of the heat source and their resulting influence in terms of the machinability improvement. Literatures on heat assisted machining using other oxy-fuel flame as a heating mechanism [6 - 8] have not investigated the heat source factors like the flame spot size/diameter in order to understand the influence of this factor on the machinability improvement. Spot size/diameter of the oxyacetylene flame have sizeable diameter to sufficiently irradiate the width of cut by a single end mill pass. This potential enable oxyacetylene flame to be very suitable for flame assisted machining with milling cutters. Consequently, investigation needs to be conducted in this

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respect. Retrofitting oxyacetylene flame with end milling is particularly lacking. This study presents the metrics for retrofitting the oxyacetylene flame with end milling cutters. The study used a regression analysis to develop a mathematical relationship of the flame spot diameter in terms of four oxyacetylene flame's heat source parameters; Focus height, oxygen pressure, acetylene pressure and resident time. The mathematical model was obtained for prediction of the flame spot size in order to control and reconcile the heat affected zone with the intended machined surface.

EXPERIMENTAL SET UP

Workpiece samples made from 316L stainless steel with composition presented in Table-1 having initial size of 400mm x 120mm x 12mm have been obtained. The samples had been sized to 60mm x 50mm x 12mm utilizing EDM wire cut having wire size of 0.25mm and tensile strength of 1000N/mm2.

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.

Experimental trials were conducted using response design to investigate the oxyacetylene flame spot size. Four controllable variables as shown in Table-2, namely; focus height, oxygen pressure, acetylene pressure and resident time were investigated as influential parameters that could determine varying flame spot size.

The experimental set up was shown in Figure-1. The actual torch would be clamped safely towards an adjustable metallic stand. The focus height would be cautiously adjusted and verified using Vernier height gauge as the ignited torch appeared to be set to the required flame settings with neutral flame regulated through the throttle valves. Preheating resides with corresponding resident time scaled using alarm alerted stop watch. Pressures of oxygen and acetylene gas are purposely changed accordingly. Other heat source variables were kept constant. Induced temperature was recorded using both contact and non-contact measurement. A multichannel acquisition system of contact measurement using Omega daqpro-5300 data logger attached to K-type thermocouples (with an operating range between -400C – 12000C) was used to accomplish continuous measurement of the induced temperature. In the same set up, a non-contact measurement set up was further incorporated using T640 Flir thermal image camera with program version 1.2. The objective of this experimental examination will be to examine the impact of these variables during preheat with oxyacetylene so as to present a scientifically based numerical approach for optimizing the oxyacetylene flame spot diameter. Design expert v6 was used to develop a second-order response surface methodology (RSM) model to generate the response surfaces under various conditions. In this way, statistical process were used to optimize oxyacetylene gas preheat for effective application. All the designs, plots and analysis have been carried out using design expert statistical software version 6.0.

Table-2. Levels of independent variables and condition for fixed variables during oxyacetylene parametric flame tests.

	Factors	Codes	Levels				
Coding of Levels			-2	-1	0	1	2
Controlled Variables	Flame height(mm)	F_h	5	7.5	10	12.5	15
	Oxygen pressure (psi)	P_{oxy}	15	20	25	30	35
	Acetylene pressure (psi)	P_{acty}	5	10	15	20	25
	Time (s)	T	3	5	7	9	11
Fixed Variables	Incidence Angle (Deg.)	Ang_{inc}	90^0				
	Nozzle Diameter (mm)	N_{dia}	6mm				

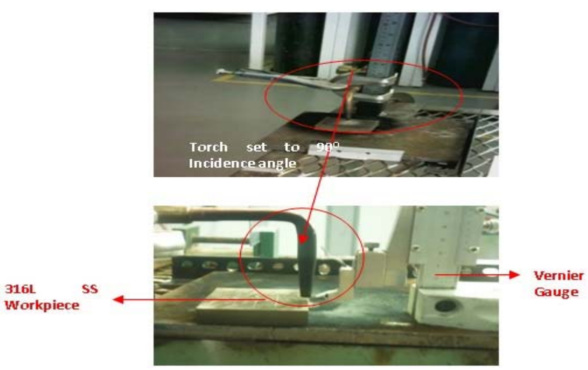

Figure-1. A set up for oxyacetylene parametric flame test.

RESULTS AND DISCUSSION

A study was conducted to investigate the influence of oxyacetylene flame parameters over the flame spot diameter as the output response. The experimental outcomes for the spot diameter are given in Table-3 according to the matrix of the design of the experiment. The empirical test observed the flame spot diameters at 30 distinct conditions. Six center point experiments were replicated in order to obtain S/N values. The influence of the four investigated heat source parameters on oxyacetylene flame spot diameter are determined and plotted as the process parameters changes from one level to another and to find out the influence of different parameters as well as their levels. Mathematical model was developed which best described the flame spot

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diameter in terms of oxyacetylene flame operating factors shown earlier in Table-2. The use of analysis of variance ANOVA approach makes it easy to analyze the results and thus make it fast to reach on the conclusion. [9].

ANALYSIS OF VARIANCE

Analysis of variance (ANOVA) table for flame spot diameter revealed the model term as 0.0001. This has fall short of the set criterion significant level (0.05), which have proven that this particular flame spot diameter model is statistically significant. Lack of fit with a value of 0.2940 was not considered significant. Hence this concluded that the model fits. The flame spot diameter model terms consist of the following significant terms (A, B, C, A^2, B^2, C^2, D^2 and AD, BD, CD), and this had been quite enough to represent a model. The codes A, B, C, and D represents focus height, oxygen pressure, acetylene pressure and resident time in the same order. The ANOVA table further portrayed these models terms being less than 0.05, each. Moreover, models terms with values greater than 0.1000 are considered non-significant and are eliminated through model reduction in order to improve the model hierarchy. The model F-Value of 24.06 is believed to be significant and there is only 0.01% chance for the model F-value this large to occur due to noise. In the aftermath of elimination of insignificant terms, the equations given below are the final equations for response surface of flame spot diameter (ŷ) quadratic model in coded terms.

$$\hat{y} = -210.78 + 19.76A + 8.62B + 4.22C - 1.04A^2 - 0.18B^2 - 0.080C^2 - 0.24D^2 + 0.27AD + 0.10BD - 0.18CD \quad (1)$$

Table-3. Experimental result of flame spot diameter.

A:Focus Height (mm)	B:Pressure Oxygen (psi)	C:Pressure Acetylene (psi)	D:Time (s)	Flame Spot (mm)
7.5	30	20	3	38
12.5	20	20	9	23
10	25	15	7	19
7.5	20	10	3	17
10	25	25	7	18
7.5	30	10	9	18
10	25	15	7	29
7.5	30	10	5	18
5	25	15	7	38
15	25	15	7	30
12.5	20	20	3	20
12.5	30	20	9	16
10	35	15	7	25
10	25	15	7	20
10	25	15	3	19
10	25	25	7	36
7.5	30	20	9	17
12.5	30	20	5	27
10	25	15	7	28
10	25	15	7	38
12.5	30	10	5	19
10	25	15	7	36
10	25	15	11	35
12.5	20	10	9	18
7.5	20	10	5	22
7.5	20	20	5	30
12.5	20	10	5	37
10	15	15	7	20
12.5	30	10	9	32
7.5	20	20	9	19

This empirical equation had been tested against the results obtained from the experimental test within the ranges given below.

5mm ≤ Target distance ≤ 15mm
15psi ≤ Oxygen gas pressure ≤ 35psi
10psi ≤ acetylene gas pressure ≤ 25psi
3secs ≤ resident time ≤ 11secs

As evident in the diagnostics plots shown in Figure-2, the residuals of the tests exists close to the straight line, which suggests that the errors are distributed randomly. The figure revealed that the residuals generally fall on a straight line implying that the errors are also distributed normally because the plot has no severe indication of non-normality or any evidence pointing to possibility of outliers [9] too.

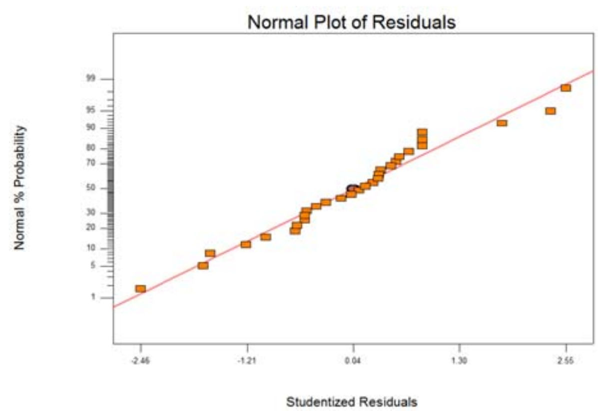

Figure-2. Diagnostics plot of residuals for flame spot diameter model of oxyacetylene flame.

The perturbation plot indicates that an increase of resident time and acetylene gas pressure increases the flame spot diameter, just as the decrease of focus height and oxygen gas pressure increases the flame spot diameter. This was also evident in the 3D response surface plot shown in Figure-3.

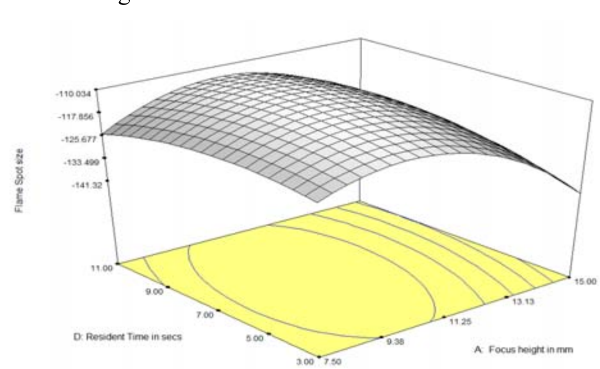

Figure-3. 3D response surface plot of a flame spot diameter model for oxyacetylene flame.

The ANOVA table of this model suggested that the focus height influences the flame spot diameter most,

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and then followed by the oxygen gas pressure, acetylene gas pressure and resident time in the same order. This fact was established in the ANOVA where the F-value of the significant model terms of the factor ‘A’ appeared higher followed by B, C then D in the same order. It was the objective of this study to identify an acceptable flame spot diameter that can be machined during a single pass with a 40mm diameter end mill tool holder. In such case, the flame spot diameter goal was set as target of 20mm in order for the heat to irradiate a dimension which will suitably overcome the strength of the substrate at the intended machined region by an end mill cutter. Lower and upper limits were set at 18mm and 22mm respectively. This means that it may be desired to have a spot diameter of 20mm but a value between 18 to 22mm may be accepted as well. The result of possible optimal solutions during preheat conditions within the range of parameters earlier presented is given in Table-4 using an optimization method developed by Derringer and Suich. The closer the desirability value is to 1, the better is the response optimization [10].

Table-4. Possible optimal solutions for flame spot diameter while preheat with oxyacetylene flame.

Optimized Preheat Conditions					
Focus Height (mm)	Oxygen Press. (Psi)	Acetylene Press. (Psi)	Resident Time (sec)	Flame Spot Dia. (mm)	Des
7.75	25.88	10.11	10.37	20	1.00
7.24	23.86	10.05	7.70	20	0.96

TOOL LIFE AND SURFACE INTEGRITY

Machining trials were conducted at room and elevated temperature conditions. Optimum heat source parameters identified in Table-4 were used during the heat assisted machining using oxyacetylene flame. Tool life and surface integrity of the machined surface was compared with dry machining conducted at the same machining conditions. Two levels cutting conditions shown in Table-5 were investigated for tool life and surface roughness.

Table-5. Machining conditions.

S/n	Machining Factors	Levels	
1	Cutting Speed (m/min)	125	79
2	Feed Rate (mm/min)	160	100
3	Depth of Cut (mm)	1	
4	Temperature Distribution	Varied	

Depth of cut was maintained as 1mm throughout the experimental tests using an uncoated WC – Co end mill insert. During dry machining at room temperature condition the shortest tool life occurred after 11.30minutes at cutting speed V=79m/min and feed rate f=160mm/min whereas longest tool life occurred after 17.60 minutes at cutting speed V=125m/min while the feed rate was f=160mm/min. However, during the flame assisted machining the tool life was 17.50minutes at cutting speed V=79m/min and feed rate f=160mm/min whereas tool life was 24.00 minutes at cutting speed V=125m/min and feed rate f=160mm/min. Generally, the wear propagation during flame assisted machining was steady and regular. Very aggressive wear was noticed while dry machining at room temperature condition as evidently shown in the Figure-4 after machining for 17minutes. Fast and fatal wear transpired towards the end of the tool life criterion 0.3mm for all the test conditions during dry machining at room temperature. Flame assisted machining was evidently discovered to increase the tool life of uncoated WC – CO end mill insert during machining AISI 316L stainless steel for all the tested conditions.

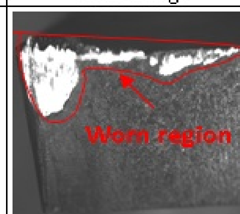
Time (min)	Room Temperature Machining	Flame Assisted Machining
17min		

Figure-4. Tool wear of uncoated WC – Co insert at V=125 m/min, f=160mm/min and DOC =1mm.

Surface roughness on the machined workpiece was captured using surface roughness tester Mitutoyo Surftest Sv-3000. The measuring set was demonstrated in Figure-5. The surface roughness has been captured at determined periods of time over the entire tool life of the inserts.

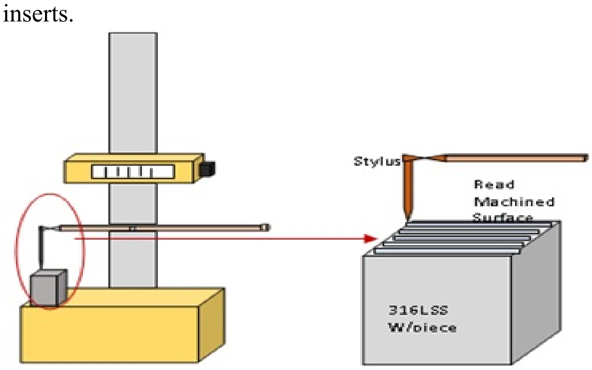


Figure-5. Set up for surface roughness captured data.

The quantitative surface topography of the machined zone during end milling at cutting speed V=125m/min and feed rate f=160mm/min had been presented in Figure-6 and 7. The profilometer read through a sampling length of 50mm utilizing a column escape line profile of 5mm apart in axial path. The line profile for the longitudinal surface topography during flame assisted machining at cutting speed V=125m/min and feed rate

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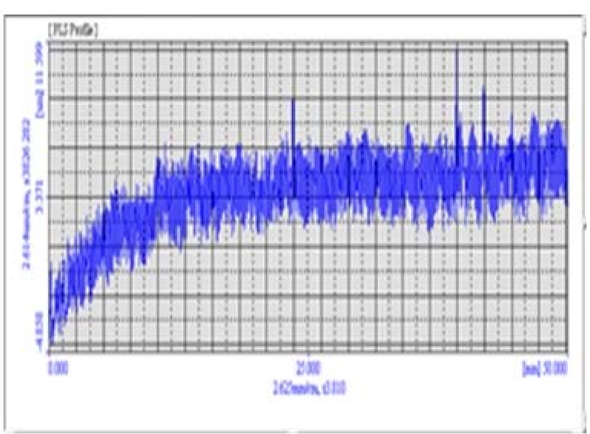
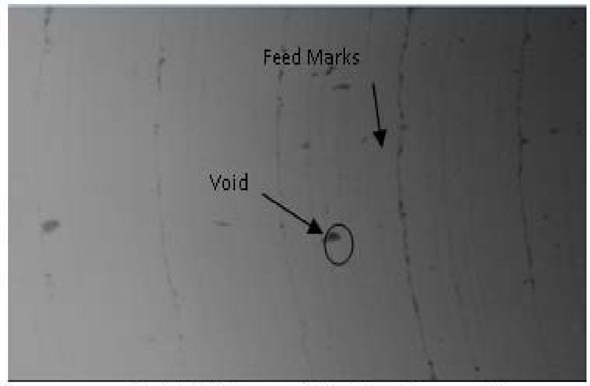
f=160mm/min was 1.64µm whereas that of dry machining at room temperature was 6.64µm. It was observed that the root mean square (r.m.s) of the two profiles varies in similar pattern and magnitude. The average surface finish reveals a pattern of increasing with increased cutting speed and decrease in feed rate. Most effective surface roughness was captured at low feed rates. It was observed that while feed rate was maintained constant at *f*=160mm/min, the machined surface finish has increased by 80 % when the cutting speed was purposely changed from 79 to 125 m/min during flame assisted machining. Apparently, similar trend with low improvement of 20 % was noticed to have occurred while dry machining at room temperature condition. Thus, it was concluded that through using preheat machining with heat sourced from oxyacetylene flame a better surface quality could be obtained. Both cutting speed and feed rate have been found to positively influence the surface roughness of AISI 316L stainless steel during either dry machining or flame assisted machining. Surface finish was observed to deteriorate with tool wear propagation. Even so, identical pattern of surface roughness propagation have occurred during both flame assisted machining and while machining at room temperature condition. Even so, the influence of preheating during end milling AISI 316L stainless steel have revealed better surface finish devoid of chip welding on the machined surface or cracks. Within the tested parameter ranges that were investigated, thermal distortion was not accrued in either case. Analysis of surface topography using scanning electron microscopy (SEM) shown in Figure-6b and 7b have proven that the flame assisted machining is a substantial economical machining process. An experimental test of micro hardness during *V*=79m/min and feed rate *f*=100mm/min machining condition on both flame assisted machining and room temperature machined surface have not revealed any irregularities. However, the test beneath the machined surface after machining at room temperature while cutting speed *V*=79/min and feed rate *f*=160mm/min, indicates an increase in the average hardness on AISI 316L stainless steel during dry machining at room temperature.



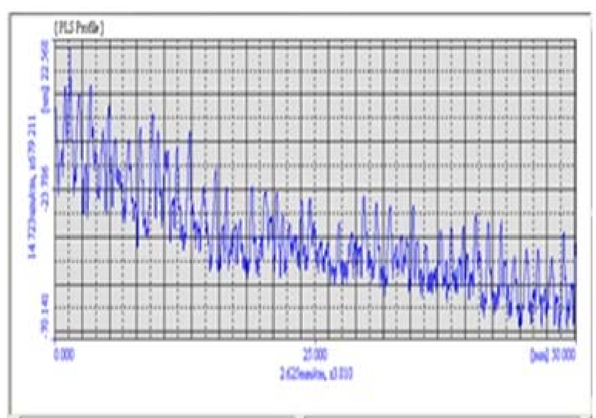
(a) Surface Roughness Profile



(b) SEM Image of Surface Topography

Figure-6. Line profile surface topography of 316L stainless steel during flame assisted machining at cutting speed *V*=125m/min and feed rate *f*=160mm/min.

Figure-8 explained precisely how hardness changes from the machined surface below the bulk material. It is typically observed that the actual hardness deviation had been notable at the immediate layer below the machined surface. The variation stabilized afterwards. It had been concluded at this condition, that AISI 316L stainless steel have work hardened during machining with uncoated WC - Co insert at room temperature. Even so, the thickness of the work hardened layer was minuscule to suspect significant microstructural distortion. Upon investigation of the value of surface roughness generated at this condition, it was established that poor surface finish can possibly relates to machining difficulties which could extends to affecting the surface integrity.



(a) Surface Roughness Profile

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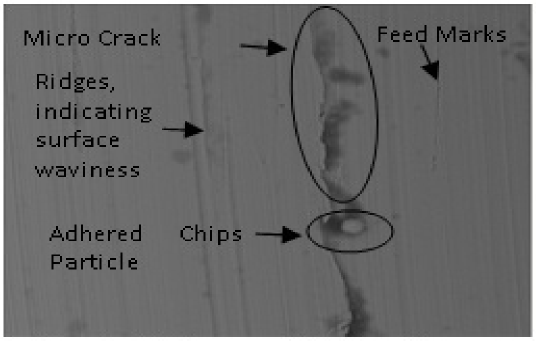

(b) SEM Image of Surface Topography

Figure-7. Line profile surface topography of 316L stainless steel during dry machining at room temperature at cutting speed *V*=125m/min and feed rate *f*=160mm/min.

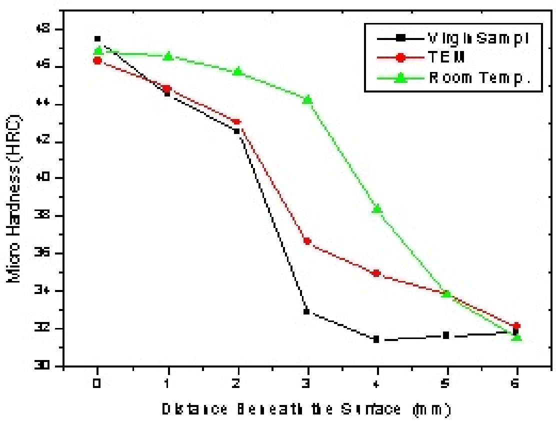

Figure-8. Micro hardness variation beneath surface of 316L stainless steel during machining at *V*=79m/min and Feed rate *f*=160mm/min.

CONCLUSIONS

Empirical model was obtained for oxyacetylene flame spot diameter when impinging on AISI 316L stainless steel for steady-state heat source in terms of four factors namely; Focus height, acetylene gas pressure, oxygen gas pressure and resident time (FOAR). The flame spot diameter was found to be influenced by all the four factors investigated.

From the result obtained for various flame parametric conditions, the largest spot diameter of 38mm was obtained at focus height 7.5mm, oxygen pressure 30psi, acetylene pressure 20psi and resident time of 3 seconds. However, an optimal flame spot diameter of 20mm was obtained at focus height 7.75mm, oxygen pressure 25.88psi, acetylene pressure 10.11psi and resident time of 10.37seconds. This optimal heat source condition was extended for application during the flame assisted machining and was found to influence and improve machinability of AISI 316L stainless steel using uncoated WC-Co end mill insert in terms of tool life, surface finish and surface integrity.

During the machining investigation, it was found that fast and fatal wear transpired towards the end of the tool life criterion 0.3mm for several test conditions during dry machining at room temperature. Flame assisted machining was evidently discovered to increase the tool life of uncoated WC – CO end mill insert during machining AISI 316L stainless steel.

The experimental results involving uncoated WC – Co insert under varying cutting conditions also reveals that preheat temperature significantly influences the surface finish on AISI 316L stainless steel. The result obtained have unveiled that oxyacetylene flame substantially enhances machinability on AISI 316L stainless steel within the scope of the cutting speed and feed rate investigated. Even so, both cutting speed and feed rate have been found to positively influence the surface roughness of AISI 316L stainless steel during either dry machining or flame assisted machining. Surface finish was observed to deteriorate with increasing tool wearing and that surface integrity is influence by surface roughness.

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