July. 2015. Vol. 7. No. 02 ISSN2305-8269
International Journal of Engineering and Applied Sciences

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OPTIMISING THE MACHINING PARAMETERS DURING STRAIGHT TURNING OF AISI 304 STAINLESS STEEL AND MILD STEEL

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ABSTRACT

In this paper, the effect of machining parameters on the surface roughness and chip formation are investigated in straight turning of mild steel and AISI 304 stainless steel. Machining experiments were planned according to the Taguchi orthogonal array L_9 (3^4). Spindle speed, feed rate, depth of cut and two different Metal Working Fluids (MWFs) coconut oil and soluble oil were selected as the machining parameters. The variation of the surface roughness and chip formation was tracked respective to the four variable control parameters depth of cut, feed rate, cutting speed and MWF. Plotting method and ANOVA were used for analyzing the results to obtain the significance on the surface roughness. For each type of steel, mathematical models were developed to predict the surface roughness. The models were validated through the confirmation experiments. The mathematical models were used to obtain the optimum parameter settings for the best surface roughness.

Keywords: ***Taguchi orthogonal array, Metal working fluid, Surface roughness***

1. INTRODUCTION

Surface roughness of a machined surface is a technical requirement in many cases and it describes the quality of the product. Hence, achieving the desired surface quality is importance for the functional behavior of the mechanical parts.[1] Many controllable and uncontrollable factors affect the surface roughness of a machined component. Some of these factors include cutting tool geometry, cutting speed, feed rate, depth of cut, microstructure of the tool and the work, rigidity of the machine tool, temperature at cutting point, etc. Much better surface finish may involve higher machining costs. Turning is a most widely used machining method to produce different components. Therefore predicting surface roughness with respect to the controllable factors during turning is important.

It has been observed that the chip morphology under different cutting speed is different. This is predominantly due to the changes in crack initiation and propagation as well as changes in flow localization in the cutting zone. Dayami et al, [2] has conducted an experimental analysis on the effect of the cutting speed on the chip morphology, and of the cutting forces in the orthogonal turning process of the titanium alloys Ti-6Al-4V. It is desirable to study the chip formation specially in turning process which are likely to generate long, continuous chips, where effective chip control is a really difficult task. Long chips can interfere with the machine tool, the work piece and the tooling and have harmful impacts upon the material removal process and the product quality and the environmental effects of the manufacturing operation (e.g. small and broken chips are much simpler to handle, transfer, put in storage and recycle). [3, 4] Various types of chips are defined in the literature and to report characteristics of chips and their form in a consistent manner International Standard Organization (ISO) has issued a standard (ISO 3685:1993) to define the chips produced. In this study chip formation was analyzed based on this standard.

July. 2015. Vol. 7. No. 02 ISSN2305-8269
International Journal of Engineering and Applied Sciences

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In this research the aim is to investigate the effect on some selected controllable factors on the surface roughness and chip formation. These factors include cutting speed, feed rate, depth of cut and the metal working fluid (MWF). When considering the MWF in machining metals, most of the MWFs are mineral oil-based fluids and these fluids increase productivity and the quality of manufacturing operations by cooling and lubricating during metal cutting and forming processes [5]. Despite their widespread use, they pose significant health and environmental hazards throughout their life cycle. [5, 6] Environmental friendly, renewable, less toxic and readily biodegradability qualities of the vegetable based MWFs make them highly attractive alternatives. Research on applicability of vegetable oil-based metalworking coolants in machining metals has been undertaken in recent years. [5, 6, 7] Therefore investigation into the effect of a suitable vegetable based MWF on surface roughness and chip formation and comparison of it with respect to a mineral oil based MWF is desired.

This paper describes the methodology, results and the discussion on investigation on chip formation and optimizing the surface roughness against the different machining parameters depth of cut, feed rate, cutting speed and MWFs (coconut oil and soluble oil) during straight turning.

2. METHODOLOGY:

Lathe machine Model CM6241X1000 with a Spindle Motor 5 Hp and a spindle speed limit 45 - 1800 rpm was selected for the machining operations. In selecting metals for the machining experiments it was necessary to find out the extensively machined metals in Sri Lanka. An online survey was done to collect the details related to material usages of the industries. Figure 1 shows the different percentages of metal usage and the responded industries machine Mild Steel (MS) and AISI 304 Stainless Steel (SS). Therefore MS and SS were selected.

The different machining parameters to be analyzed under this study include depth of cut, feed rate, cutting speed and MWFs. It was planned to find a suitable vegetable based oil and a mineral oil based soluble oil for the experiments as MWFs. In order to select suitable vegetable based oil, a market survey was carried out and ten different vegetable oils, as shown in Table 1, were collected.

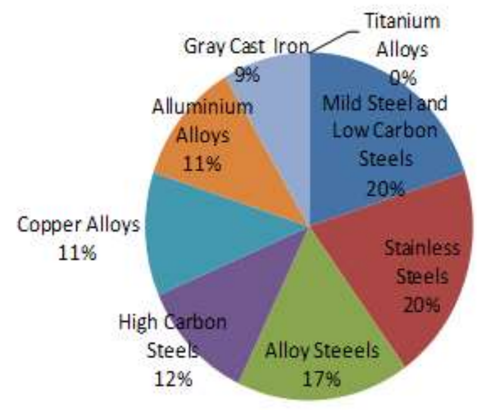

Figure 1 Comparison of machining metal usage in local industries

Considering the price and the availability of oils, coconut oil, white coconut oil and margosa oil were selected for testing specific heat and flash point. White coconut oil which had a higher specific heat and a higher flash point was selected as the vegetable based MWF for experimentation. It was decided to use it with the injecting method with a pump 0.1 kW and aerated spray method at a pressure 7 bar. According to the Taguchi's Orthogonal Array L9 (3^4) machining experiments were conducted for both SS and MS and surface roughness values were measured using the TR200 Hand- held roughness tester. Further chip samples were collected after each experiment and photographs were taken.

3. RESULTS AND DISCUSSION:

After each experiment chips were collected and some of the collected chips are shown in Figure 2, showing the variety in their form.

Further for each experiment three surface roughness values were measured and the average of the three was calculated. Table 3 shows the experimental parameter settings and the measured surface roughness values and chip form classification according to ISO 3685: 1993 standard. Subsections 3.1 and 3.2 describe the analysis of chip formation and the surface roughness for both steel types and sub section 3.3 explains the model fitting and optimization of machining parameters for minimum surface roughness.

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Table 1: Selected oils from the local market

Name	Price per 750ml(LKR)	Availability	Remarks
Virgin Coconut Oil	580	Poor	
White Coconut Oil	260	Good	Selected for further testing
Cinnamon Oil	2800	Poor	
Castor Oil	620	Poor	
King Coconut Oil	680	Good	
Coconut Oil	220	Good	Selected for further testing
Sesame Oil	580	Poor	
Margosa Oil	400	Poor	Selected for further testing
Mustard Oil	560	Poor	
Domba Oil	1200	Poor	

Table 2: Specific Heat and Flash Point Values

Candidate Oil	Specific Heat/ (kJ/kg^{o}C)	Flash Point/ ^{o}C	Remarks
White Coconut Oil	1633.30	230	Selected as the MWF
Coconut Oil	1403.30		Rejected due to low Specific Heat
Margosa Oil	1656.88	103	Rejected due to low Flash Point

Figure 2: Some collected chips, showing the variety in their forms

3.1 Chip Formation

The collected chips are classified (in column 7 in Table 3) according to a basic numerical coding as described in ISO 3685:1993 standard. The basic coding system composes two digits which relate to the basic chip characteristics. For example 2.2 is the code to denote a short tubular chip. The form (shape and color) and thickness of the chips directly and indirectly indicate the nature of chip–tool interaction influenced by the machining environment. Segreto, et al [9] have further classified the chip types described in ISO 3685:1993 standard as "Favourable" and "Unfavourable" chips for machining as shown in Table 4.

In the study, the collected chips were further categorized (in column 8 in Table 3) according to the classification described in Table 4. More Favourable chip types were observed during machining mild steel compared with stainless steel. The soluble oil was used for the first three machining experiments for both steel types and "Favourable" chips were produced only for experiment 1. However coconut oil spay and coconut oil injection method in machining experiments 4 to 9 shows more "Favaourable" chips during machining mild steel compared with stainless steel. More straight and tabular snarled chips could be observed during machining stainless steel. Stainless steel has much lower thermal conductivity and higher ductility than conventional steel. The ingredients added to improve its corrosion resistance and tensile strength, especially chromium, nickel and molybdenum, give it the highest yield strength. The results during turning are more friction, higher cutting forces and therefore higher temperatures with consequential smearing tendency and work-hardening of the component surfaces. This can be the reason for

 ISSN2305-8269
International Journal of Engineering and Applied Sciences

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more "Unfavourable" chips for machining stainless steel compared with mild steel.

3.2 Surface Roughness

Average results for each parameter was calculated and individual factor plots were drawn as shown in Figure 3 to 6. ANOVA table was created with the average test results and pooling-up strategy was used for estimating the error variances. For the mild steel the most minimum contribution, spindle speed is taken as pooled error. The highest, mean and lowest contribution to the surface roughness values are indicated as feed rate, MWF and depth of cut respectively. For stainless steel the most minimum contribution, depth of cut is taken as the pooled error and the highest, mean and lowest contribution on the surface roughness are indicated as feed rate, spindle speed and MWF respectively.
In Figure 4 it indicates that better surface roughness values are for the higher spindle speed values. Generally the surface roughness values inversely proportional to the spindle speed according to Figure 4. In the case of feed rate it has better surface roughness values at the lowest feed rate values in machining of both mild steel and stainless steel. So that from Figure 3 the proportional variation can be recognized for the feed rate on the effect to the surface roughness. Considering Figure 5 a random variation but a similar pattern for both metal types is indicated for the cutting depths on surface roughness.
Therefore selecting the best values for the selected parameters to obtain the minimum surface roughness is a crucial step in machining.

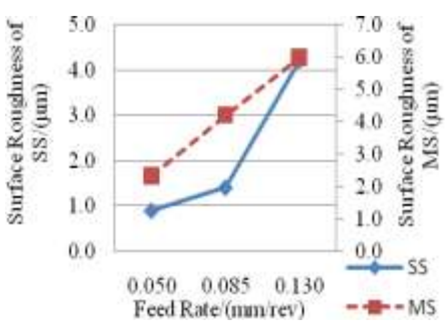

Figure 3: Surface roughness with respect to feed rate

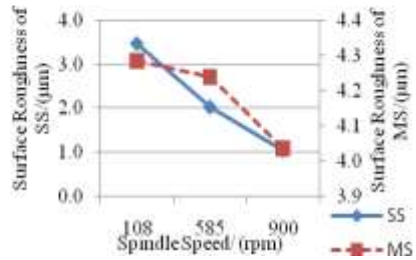

Figure 4: Surface roughness with respect to spindle speed

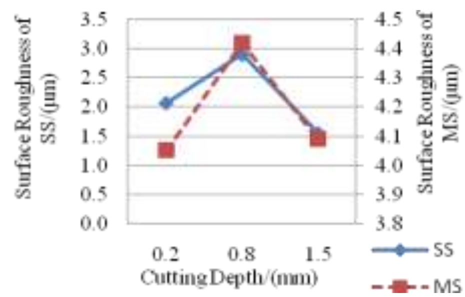

Figure 5: Surface roughness with respect to depth of cut

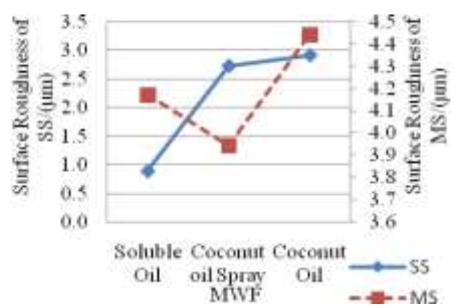

Figure 6: Surface roughness with respect to MWF

3.3 Model fitting and Optimization

Optimization of the machining conditions is necessary in order to find the optimal values for selected parameters. For this task empirical models were built. The results obtained from the machining experiments were analysed and polynomial models were fitted to represent the machining results. Polynomial models were fitted using the least square regression analysis method.
Consider a first order polynomial model, which can be represented in matrix notation,

$$\{y\} = [X]\{\beta\} + \{\varepsilon\} \quad (1)$$

ISSN2305-8269
International Journal of Engineering and Applied Sciences

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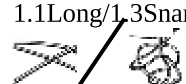
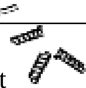
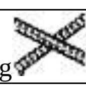
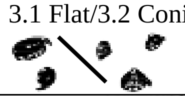
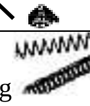
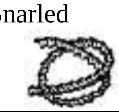
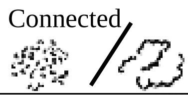
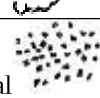
Table 3: Surface Roughness and Chip Form

Experiment No	Parameter settings [MWF, spindle speed/(*rpm*), feed rate/(*mm/rev*) & depth of cut/(*mm*)]	Ra / (µm)				Chip form according to ISO 3685	Favourable /Unfavourable [Segreto et al, 2012]
		1	2	3	Avg		
Mild Steel							
1	Soluble oil, 108, 0.05, 0.2	1.031	2.168	3.646	2.282	6.2	F
2	Soluble oil, 585, 0.085, 0.8	3.219	4.542	5.709	4.490	4.1	U
3	Soluble oil, 900, 0.13, 1.5	6.234	4.925	6.074	5.744	4.3	U
4	Coconut oil spray,108,0.085, 1.5	4.372	4.097	3.460	3.976	7.0	F
5	Coconut oil spray, 585, 0.13, 0.2	5.986	4.682	6.377	5.682	4.1	U
6	Coconut oil spray, 900, 0.05, 0.8	2.148	2.644	1.726	2.173	4.2	F
7	Coconut oil, 108, 0.13, 0.8	6.269	6.840	6.681	6.597	4.2	F
8	Coconut oil, 585, 0.05, 1.5	3.498	2.360	1.779	2.546	4.2	F
9	Coconut oil,900, 0.085, 0.2	3.896	3.994	4.672	4.187	4.1	U
Stainless Steel							
1	Soluble oil, 108, 0.05, 0.2	0.867	0.939	0.572	0.793	4.2	F
2	Soluble oil, 585, 0.085, 0.8	0.680	0.668	0.732	0.694	2.3	U
3	Soluble oil, 900, 0.13, 1.5	1.244	1.208	1.064	1.172	4.1	U
4	Coconut oil spray,108,0.085, 1.5	2.528	2.819	2.518	2.622	1.1	U
5	Coconut oil spray, 585, 0.13, 0.2	4.517	4.534	4.498	4.516	3.1	U
6	Coconut oil spray,900,0.050, 0.8	1.161	1.031	0.922	1.038	2.3	U
7	Coconut oil, 108, 0.13, 0.8	5.352	7.914	7.652	6.973	1.1	U
8	Coconut oil, 585, 0.05, 1.5	0.931	0.876	0.764	0.857	4.2	F
9	Coconut oil,900, 0.085, 0.2	0.915	0.871	0.918	0.901	4.1	U

Table 4 ISO Chip form further classification [9]

Cutting		Favourable	Unfavourable	
Straight	1 Ribbon Chips	1.2 Short 		1.1Long/1.3Snarled 
Mainly up curling	2 Tabular Chips	2.2 Short 	2.1 Long 	2.3 Snarled 
	3 Spiral Chips		3.1 Flat/3.2 Conical 	
Mainly side curling	4 Washer type Chips	4.2 Short 	4.1 Long 	4.3 Snarled 
Up and side curling	5 Conical Helical Chips	5.2 Short 	5.1 Long 	5.3 Snarled 
	6 Arc Chips	6.2Loose/6.1 Connected 		
	7-8 Natural Broken Chips	7 Elemental 		8 needle 

ISSN2305-8269
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Where $\{y\} = \begin{Bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{Bmatrix}_{n\times 1}$ is the surface roughness obtained for machining experiment, i

$\{\beta\} = \begin{Bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_k \end{Bmatrix}_{(k+1)\times 1}$ β_0 and β_i, $i = 1,2,\cdots,k$ are unknown parameters

$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{Bmatrix}_{n\times 1}$ represents experimental error and

$[X] = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1k} \\ 1 & x_{21} & x_{22} & \cdots & x_{2k} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{n1} & x_{n2} & \cdots & x_{nk} \end{bmatrix}_{n\times(k+1)}$ x_{ij} is the parameter setting of design parameter x_j at machining experiment i.

Rearranging equation (1),

$$\{\varepsilon\} = \{y\} - [X]\{\beta\} \tag{2}$$

The parameter estimates $\{b\}$, for the vector $\{\beta\}$ are found by minimising sum of error squares. The fitted polynomial model is a function of selected parameters, depth of cut, feed rate, cutting speed and MWF.

In this study equation (3) and (4) shows the two mathematical models fitted to predict the surface roughness for both types of steels.

$$R_{aMS} = 0.4907 - 1.3203A + 0.364A^2 + 0.0004B + 77.5393C - 175.6349C^2 + 1.4541D - 0.838D^2 \tag{3}$$

$$R_{aSS} = -1.2468 + 4.32A - .0.827A^2 - 0.0029B - 66.4149C + 599.828C^2 + 3.9373D - 2.5512D^2 \tag{4}$$

Where, R_{aMS}, R_{aSS}, A, B C and D are Surface Roughness of Mild steel, Surface roughness of Stainless steel, Metal Working Fluid, Spindle Speed, Feed Rate and Depth of Cut respectively.

Confirmation experiments were conducted and the results were compared with the values obtained from the mathematical models as shown in Table 5. The validated two mathematical models were used for optimization by setting it as objective functions. Best values for the parameters were selected to minimize the objective function or the surface roughness. The optimisation tool box in Mat LAB was used for finding the optimal values shown in Table 6. The optimal values for feed rate and the depth of cut is same for both steel types. According to the optimization results during machining mild steel, coconut oil act as the best MWF whereas during machining stainless steel soluble oil act as the best MWF. This phenomenon is even observed in chip formation analysis and optimization results confirm the chip analysis results.

Table 5: Mathematical model verification

MWF	Spindle speed	Feed rate	Depth of cut	Experimental value	Value from mathematical model
For Stainless Steel					
Soluble oil	255	0.13	1.5	6.4	6.3
Coconut oil spray	385	0.05	0.2	2.2	2.1
Coconut oil	900	0.05	0.2	2.5	2.8
For Mild Steel					
Soluble oil	900	0.05	0.2	0.6	0.4
Coconut oil spray	108	0.13	1.5	4.7	4.6
Coconut oil	585	0.13	1.5	3.2	3.3

Table 6: Optimal Parameter Settings

Parameter	For Mild Steel	For Stainless Steel
Spindle Speed/ (rpm)	108	900
Feed rate/ (mm/rev)	0.05	0.05
Depth of cut/ (mm)	0.2	0.2
MWF	Coconut oil	Soluble oil

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4.0 CONCLUSION

Chip formation was analysed and categorized according to ISO 3685:1993 standard. More straight and tabular snarled chips (considered as "Unfavourable" chips) could be observed during machining stainless steel. Stainless steel has much lower thermal conductivity and higher ductility than conventional steel. The results during turning are more friction, higher cutting forces and therefore higher temperatures with consequential smearing tendency and work-hardening of the component surfaces which cause to get more "Unfavourable" chips for machining stainless steel compared with mild steel.

Validated mathematical models were developed to predict the impact of each control variable on the surface roughness for mild steel and AISI 304 stainless steel. The models were used for selecting optimal parameter settings to get minimum surface finish during machining.

For both types of steels, the optimum parameter setting for feed rate and depth of cut are the same and they are 0.05 mm/rev and 0.2mm respectively. According to optimum results for mild steel, the optimised surface roughness gives when using coconut oil as the MWF. But for stainless steel the optimum surface roughness gives when using soluble oil as the MWF. Further it can be concluded that better surface roughness gives for mild steel at low speeds with coconut oil whereas for stainless steel at high speeds with soluble oil.

Acknowledgement

The authors are grateful to the Faculty of Engineering, University of Ruhuna, Sri Lanka for the provision of funds through the annual research grants 2013 and 2014.

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