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OPTIMISATION OF CUTTING TEMPERATURE DURING THE TURNING OPERATION OF AISI 1330 ALLOY STEEL WITH HSS CUTTING TOOL USING VEGETABLE OIL-BASED COOLANTS

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Abstract: In this study, optimisation of cutting temperature was evaluated during turning of AISI 1330 alloy steel using HSS cutting tool. Experiments were conducted using L_{27} (3^4) orthogonal array and each experiment was repeated three times and each test uses a new cutting tool to ensure accurate readings of the surface roughness. The statistical methods of signal to noise (S/N) ratio and the analysis of variance (ANOVA) were applied to investigate the effects of cutting speed, feed rate and depth of cut on cutting temperature. The cutting temperature was optimized using the regression equation and confirmation test show acceptable percentage error.

Keywords: Cutting temperature, optimisation, cutting fluid, machining

1. INTRODUCTION

Machining is a process in which a tool removes material from the surface of a less-resistant body, through relative movement and application of force. The material removed, called chip, slides on the face of the tool, known as tool rake face, submitting it to high normal and shear stresses and, moreover, to a high coefficient of friction during chip formation (Ackroyd et al, 2001). Machining of steel inherently generates high cutting temperature, which not only reduces tool life but also impairs the product quality. Conventional cutting fluids are ineffective in controlling the high cutting temperature and rapid tool wear. Further, they also deteriorate the working environment and lead to general environmental pollution. Though cutting fluids are widely employed to carry away the heat in machining, their usage poses threat to ecology and the health of workers. Hence, there arises a need to identify eco-friendly and user-friendly alternatives to conventional cutting fluids (Krishna et al, 2010). Most of the mechanical energy used to form the chip becomes heat, which generates high temperatures in the cutting region. High cutting temperature, which adversely affects tool life, dimensional and form accuracy, surface integrity of the product, inherently characterizes high-speed machining. In industry, such high cutting temperature and its detrimental effects are generally reduced by proper selection of process parameters, proper selection application of cutting fluid, and using heat and wear resistance cutting tool materials like carbides, coated carbides and high-performance ceramics. But high performance ceramics (CBN and diamond) are extremely heat and wear resistive, but those are too expensive, and are justified for very special work materials and requirements where other tools are not effective (Shaw et al, 1951; Merchant, 1958; Cassin and Boothroyed, 1965). To minimize the effect of friction and the resultant heat on tool life, and the consequent effect on the integrity of the machined surface, cutting fluid is used as a means of conducting heat from the cutting zone (Abu, 2011). Vegetable oil-based emulsions are also a part of recent research to produce stable emulsions to use as metalworking fluids and in other applications (Alander and Warnhein, 1989). Lawal et al. (2012) show that a better performance can be achieved during machining processes using vegetable oil-based metalworking fluid. Vegetable oil-based cutting fluids are environmentally friendly, renewable, less toxic and economical in the reduction of the waste treatment costs due to their inherently higher biodegradability (Cetin et al, 2011). Vegetable oil-based cutting fluids seem to be the best alternatives to mineral oil based cutting fluids due to certain inherent chemical properties and their biodegradability ability. The better performance of vegetable oil-based cutting fluids can be traced to its high flash point, high viscosity index, high lubricity and low evaporative loss compared to mineral oils (Adhvaryu and Erhan, 2002). Poor oxidative and hydrolytic stability, high temperature sensitivity of tribological behaviour and poor cold flow properties are the limitations of vegetable oils for lubricants (Erhan and Asadauskas, 2000). However, these shortcomings in the vegetable oils can be addressed with addition of chemical additives such as emulsifier, corrosion prevention, pH regulator, binding, anti-foaming, odour prevention, flash point improver, spreading and wetting to improve its functions as lubricant. Suresh et al (2012) examined the effect of dry cutting on surface roughness, tool wear, cutting force, machine power during machining of AISI 4340 steel with cemented carbide tools. Cydas (2010) studied the effect of dry cutting on surface roughness, tool flank wear and temperature during turning of AISI 4340 steel with ceramic tools. Dhar et al. (2006) evaluated tool wear and surface roughness under dry, wet (conventional) and MQL during turning of AISI 4340 steel with coated carbide tools. Cutting fluids based on vegetable oils showed better performance than mineral oils. In this study, the effect of false walnut oil, groundnut oil based cutting fluids and commercial cutting fluid on cutting temperature during turning of AISI 1330 alloy steel using high speed steel tool was investigated.

2. MATERIALS AND METHODS

The materials and methods described for the formulation of cutting fluids and turning process have already been published earlier (Onuoha et al, 2016) except the cutting temperature method. Onuoha et al. (2016) used the same emulsion cutting fluids and turning process to investigate the effect of cutting fluids on surface while turning AISI 1330 alloy steel with HSS tool.

2.1 Materials

The following materials were used in the formulation of oil-in water emulsion cutting fluids:

2.1.1 Cutting fluids: - Cutting fluids used in this study were sourced from two vegetable oils – false walnut and groundnut oils. Mineral based cutting fluid was used as control experiment. False walnut oil was sourced from Jiblik village in Plateau state, and groundnut oil was sourced from Minna in Niger State both in Nigeria. The formulation of oil- in - water cutting fluids were done using full factorial experimental method for each of the oils. The following additives were used:

(i) Emulsifier (polyoxyethylene sorbitan monostrate or Tween-80)
(ii) Antioxidant (butylated hydroxytoluene- BHT)
(iii) Corrosion Inhibitor (banana sap obtained from banana stem –*musa acuminate* plant (El-Sayed et al, 2001).
(iv) Biocide (triazine) and distilled water (laboratory made).

Table 1 shows the characteristics of the formulated emulsion cutting fluids from false walnut and groundnut oils, and commercial cutting fluid (UNICUT Soluble Oil, NKO 287E716K).

Table 1: Characteristics of emulsion cutting fluids

S/N	Properties	Walnut based cutting fluid	Groundnut based cutting fluid	Commercial (mineral based cutting fluid)
1	pH value	9.40	9.72	8.07
2	Viscosity	1.98	2.89	0.144
3	Corrosion level	Corrosion resistant	Corrosion resistance	Corrosion resistance
4	Stability	Stable	Stable	Stable
5	Colour	Amber	Milky	Milky

2.1.2 Workpiece: - An annealed AISI 1330 alloy steel workpiece material of 45 mm diameter and 500 mm long sourced from Ajaokuta Steel Company, Ajaokuta-Nigeria was used in this study. The elemental analysis of the material was determined at the National Metallurgical Development Centre, Jos, Nigeria. The hardness value of the material is 30.1HRC with the composition percentages by weight show in Table 2:

Table 2: Composition of AISI 1330 alloy steel

Element	C	Si	Mn	Cr	Ni	Cu	W	P	S	Fe
% weight	0.296	0.461	1.230	0.060	0.022	0.080	0.011	0.040	0.023	97.70

2.1.3 Cutting tool:- High speed steel (HSS), AISI M-42 type with the following geometry: nose radius of 0.5 mm, back rake angle of 6°, side rake of 10°, end cutting edge of 12° and side cutting edge of 12°.was used in this study

2.2 METHODS

2.2.1 Experimental design

Taguchi method is an experimental design technique which is useful in reducing the number of experiments dramatically, by using orthogonal arrays to minimize the effects of the factors from being out of control. The basic philosophy of the Taguchi method is to ensure quality in the design phase. The greatest advantages of the Taguchi method are to decrease the experimental time, to reduce the cost and to find out significant factors in a shorter time period (Sanyılmaz, 2006). The most reliable of Taguchi's techniques is the use of parameter design, which is an engineering method for product or process design. It focuses on determining the parameter settings producing the best levels of a quality characteristic with minimum variation. The most important stage in the design of an experiment lies in the selection of control factors. As many factors as possible should be included in order to make possible to identify non-significant variables at the earliest opportunity (Aslan, et al, 2007; Ghani et al, 2004). Taguchi creates a standard orthogonal array to accommodate this requirement. Taguchi used the signal-to-noise (S/N) ratio as the quality characteristic of choice. Signal to noise ratio is used as a measurable value, instead of standard deviation, because as the mean decreases, the standard deviation, also decreases and vice versa ((Aslan, et al, 2007; Ghani et al, 2004; Park, 1996). The S/N ratio characteristics can be divided into three categories, given as nominal is the best characteristic, smaller is the better characteristic and larger is the better characteristic. In this study, experimental set up was based on design of experiment (DOE) via Taguchi method, and four variables namely; cutting speed, feed rate, depth of cut and cutting fluids. These were considered for experimentation. Hence, there were four input parameter and for each parameters, three levels were assumed as shown in Table 3. For a four-factor-three-level experiment, Taguchi specified L_{27} (3^4) orthogonal array for experimentation. The confidence level specified for the analysis is 95%.

Table 3: Machining parameters and their levels

Factor	Unit	Level 1	Level 2	Level 3
Cutting speed	m/min	28	35	42
Feed rate	mm/rev	0.124	0.178	0.249
Depth of cut	mm	0.3	0.6	0.9
Viscosity of cutting fluids	mm^2/s	1.986	2.898	0.144

2.2.2 Turning conditions

The machining experiment involved the turning of the workpiece on a manually operated POTISJE PA 25 centre lathe, using a HSS cutting tool. In each experimental run, a fresh cutting tool was used for a fixed cutting time of 20 minutes.

The cutting fluid was applied using conventional (flood) method with a flow rate of 500 ml/min. On the prediction of the influence of cutting fluid on the temperature distribution in metal removal. Childs et al (1988) postulated that the effectiveness of heat removal from the cutting zone was dependent on two factors.

namely, the flow rate of the cutting fluid and the application direction of the fluid. Early studies on characterizing temperature were carried out by experimental method using a variety of techniques such as: (a) thermocouple (tool-work or embedded thermocouples), (b) infrared imaging, and (c) micro-structural change. This study employed the infrared thermometer method to measure the temperature generated at the cutting zone. The average of three readings taken per sample were used for the analysis of the corresponding signal-to-noise (S/N) ratio, and the smaller the better the characteristics as represented in equation (1) was used for the analysis.

$$\eta = -10 \log \frac{1}{n}\left(\sum y_i^{\,2}\right) \tag{1}$$

where η is the S/N ratio for "the smaller-the-better" case, y_i is the measured quality characteristic for the i^{th} repetition and n is the number of repetitions in a trial.

3. RESULTS AND DISCUSSION

The input factors and the response obtained from the experiments are shown in Table 4. The results of the experiments were subjected to the signal-to-noise (S/N) ratio and analysis of variance (ANOVA) to determine the optimum and significant factors that affect the cutting temperature in this study.

Table 4: Experimental data obtained from machining of AISI 1330 alloy steel

Trial	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Viscosity of cutting fluids (mm²/s)	Cutting Temperature (°C)
1	28	0.124	0.3	1.986	35.33
2	28	0.124	0.3	2.898	34.63
3	28	0.124	0.3	0.144	34.65
4	28	0.178	0.6	1.986	36.15
5	28	0.178	0.6	2.898	36.50
6	28	0.178	0.6	0.144	35.56
7	28	0.249	0.9	1.986	37.45
8	28	0.249	0.9	2.898	36.76
9	28	0.249	0.9	0.144	36.78
10	35	0.124	0.6	1.986	36.90
11	35	0.124	0.6	2.898	36.28
12	35	0.124	0.6	0.144	36.33
13	35	0.178	0.9	1.986	37.45
14	35	0.178	0.9	2.898	37.30
15	35	0.178	0.9	0.144	37.34
16	35	0.249	0.3	1.986	37.78
17	35	0.249	0.3	2.898	37.65
18	35	0.249	0.3	0.144	37.66
19	42	0.124	0.9	1.986	38.05
20	42	0.124	0.9	2.898	37.48
21	42	0.124	0.9	0.144	37.52
22	42	0.178	0.3	1.986	38.60
23	42	0.178	0.3	2.898	38.12
24	42	0.178	0.3	0.144	38.16
25	42	0.249	0.6	1.986	39.45
26	42	0.249	0.6	2.898	39.33
27	42	0.249	0.6	0.144	39.41

3.1 Analysis of variance of cutting temperature

The ANOVA result is shown in Table 5 and it was used to study the significance of each input parameter on the cutting temperature. The results showed the contributions of each of the input parameters as follows: cutting speed (66.54%), feed (27.99%), depth of cut (1.16%), and cutting fluid viscosity (2.55%) respectively. The above figures showed that the cutting speed had the highest significance on the temperature generated during machining following by the feed. This is in agreement with literature (Ojolo et al, 2008). The depth of cut and the cutting fluid type had little or no significance to the temperature.

Table 5: ANOVA analysis for cutting temperature

Factor	Unit	DF	SS	MS	F-ratio	% P
Cutting speed	m/min	2	30.242	15.21	456.442	0.6654
Feed rate	m/rev	2	12.720	6.36	191.983	0.2799
Depth of cut	mm	2	0.730	0.37	1.1169	0.0161
Cutting fluid type	mm^2/s	2	1.160	0.58	17.50785	0.0255
Error		18	0.596	0.331	0.0131	
Total		26	45.4483			

The result of this study is in agreement with a similar study carried out by Krishna et al (2010) in the investigation of the performance of nanoboric acid powder suspension in SAE 40 oil and coconut (vegetable) oil in the turning of AISI 1040 steel with cemented carbide. Their results showed that the cutting speed and the feed influenced the increase of the cutting temperature irrespective of the lubricant. The result also showed that the cutting temperature was found to be less with the coconut vegetable oil as compared to the SAE 40 oil.

3.1 Signal – to- Noise (S/N) ratio analysis

Table 6 shows the corresponding S/N (dB) ratio for the cutting temperature. Since the smaller- the –better- value of the response is desirable, the performances of the three cutting fluids were analyzed using Taguchi optimization process. This is based on the principle of static problems of "smaller-the-better" characteristic (S/N) ratio for the cutting temperature. For ease of computing and analyzing the ratios, statistical analysis software (Minitab-14), widely used in engineering applications was used to investigate the optimal parameters for the cutting temperature.

Table 6: Signal-to- Noise ratio values for the responses

Trial	Temperature (°C)	Signal to Noise for temperature (dB)
1	35.33	-30.9629
2	34.63	-30.7891
3	34.65	-30.7941
4	36.15	-31.1622
5	36.50	-31.0046
6	35.56	-31.0192
7	37.45	-31.4690
8	36.76	-31.3075
9	36.78	-31.3122
10	36.90	-31.3405
11	36.28	-31.1934
12	36.33	-31.2053
13	37.45	-31.4690
14	37.30	-31.4342
15	37.34	-31.4435
16	37.78	-31.5452
17	37.65	-31.5153
18	37.66	-31.5176
19	38.05	-31.6071
20	37.48	-31.4760
21	37.52	-31.4853
22	38.60	-31.7318
23	38.12	-31.6231
24	38.16	-31.6322
25	39.45	-31.9209
26	39.33	-31.8945
27	39.41	-31.9121

The main effects plot for the signal-to-noise (S/N) ratio for the temperature at the cutting zone according to the Taguchi L_{27} orthogonal array is shown in Figure 1. From the plot, it can be observed that the optimal cutting parameters resulting in the least temperature are 28 m/min for the cuting speed (level 1), 0.124 mm/rev for the feed (level 1), 0.3mm for the depth of cut(level 1), and 2.898 mm^2/s for the cutting fluid type (level 3). The vegetable oil with 2.898 mm^2/s viscosity had the best influence on the temperature at the cutting zone than the other cutting fluids.

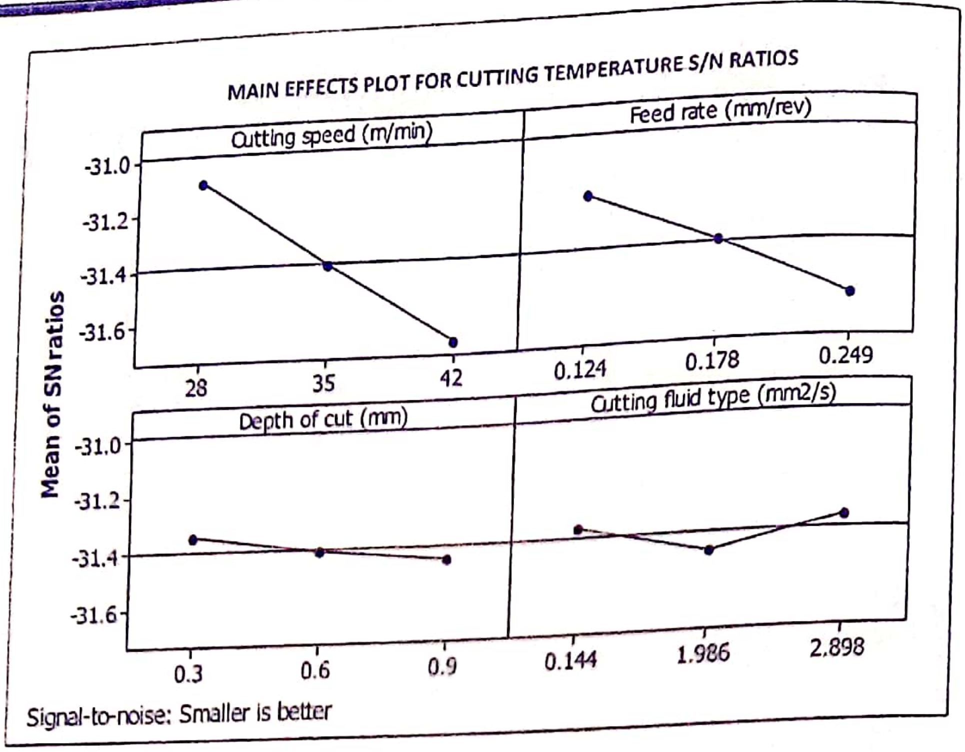

Figure 1: Main effects plot for S/N ratio for temperature

The ranking of the cutting fluids according to their effectiveness are: groundnut oil base cutting fluid, commercial cutting fluid and the atili cutting fluid respectively. The main effects plot showed that the lower levels of the cutting speed, feed and depth of cut had favourable influence on the level of the temperature at the cutting zone. Also, the viscosity of the groundnut oil based emulsion cutting fluid had a good reduction effect on the temperature. This can be attributed to the film strength of the groundnut oil emulsion which had a reduction effect of the friction associated with shearing and deformation of the chip during machining. According to Callahan and Habbard (2004), about 70-75% of the heat generated during machining is associated with the shearing action and deformation of the chip and about 25-30% is associated with the friction of the chip, sliding over the rake face of the cutting tool. The groundnut oil emulsion was able to reduce the temperature through the combination of its cooling and lubricating properties. It can also be observed from the results that for a given level of cutting speed, the temperature increased as the feed increased for each cutting fluid. Despite the use of cutting fluids for machining with HSS cutting tools, the tips easily exceed their critical temperature range leading to softening and rapid wear of the tip with a concurrent loss of finish and size of product (Sluhan, 1994).

3.2 Optimisation Process

The model for the machining parameters (cutting speed, feed, depth of cut, and cutting fluid type) were obtained from regression analysis using the MINITAB 14 software. The optimal values of the input parameters obtained from the main effect plot for cutting temperature were used to optimise the process using the regression equation (2). Confirmation experiment was conducted and results shown in Table 7. All the values of R^2 obtained for cutting temperature agreed with the regression model. According to Montgomery et al. (1998), R^2 is a value of correlation coefficient in any multiple linear regression analysis and should be within 0.8 and 1.0.

$$T_m = 27.8 + 0.185v + 13.4f_r + 0.661d + 0.0213c_{ft} \quad (2)$$

when $v = 28$ m/min., $f = 0.124$ mm/rev., $d = 0.3$mm, and $c_{ft} = 2.898$ mm^2/s

$T_m = 27.8 + 0.185(28) + 13.4(0.124) + 0.661(0.3) + 0.0213(2.898)$ °C $= 34.9016$ °C

$R^2 = 96.10\%$ and R^2 (adjusted) $= 95.40\%$

Table 7: Confirmation test percentage error

Response	Calcualted value	Experimental value	Percentage error (%)
Temperature (°C)	34.90	34.63	0.79

4.0 CONCLUSION

This study investigated the formulation and performance of false walnut and groundnut oil based oil-in-water emulsion cutting fluids. The results showed that these vegetable oil-based cutting fluids are much better than the mineral oil based cutting fluids in the machining of AISI 1330 alloy steel. The optimal machining parameters for cutting temperature show that the condition for machining AISI 1330 alloy steel with HSS tool is best with moderate cutting speed, low feed rate and depth of cut. The use of some natural additives such as banana sap as corrosion inhibitor is an innovation which helped to make the formulation operator and environmentally friendly with minimal disposal costs.

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