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Determining the Effect of Cutting Fluids on Surface Roughness in Turning AISI 1330 Alloy Steel Using Taguchi Method

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Abstract

Taguchi method has been employed to investigate the effects of cutting fluids on surface roughness in turning AISI 1330 alloy steel, using manually operated lathe machine. Experiments have been conducted using L_{27} (3^4) orthogonal array and each experiment was repeated three times and each test used a new cutting tool, High Speed Steel (HSS), 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 effects of cutting speed, feed rate and depth of cut on surface roughness under different cutting fluids. Minitab 14 software was used to analyze the effect of variables on the surface roughness. Results obtained indicated that optimal variables for the minimum surface roughness were cutting speed of 35 m/min (level 2), feed of 0.124 mm/rev (level 1), depth of cut of 0.3 mm (level 1) and a cutting fluid with a viscosity of 2.898 mm^2/s (level 3). Hence, the optimal parameters to obtain better surface roughness of the workpiece material were obtained when groundnut oil based cutting fluid was used. Analysis of variance shows that feed rate has the most significant effect on surface roughness.

Keywords

Taguchi Method, Surface Roughness, Turning Process, Cutting Fluid

1. Introduction

Machining processes result in the generation of enormous heat due to the friction between the cutting tool and

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the workpiece material, and between the tool face and the chips gliding over it [1]. This, to a great extent, affects the tool life and the surface integrity of machined products. 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 [2]. Vegetable oil-based emulsions are also a part of recent research to produce stable emulsions to use as metalworking fluids and in other applications [3]. A comprehensive review of the application of vegetable oil-based metalworking fluids in machining ferrous metals by Lawal *et al.* [4] shows 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 [5]. Machining industry concerned with the development of preventive legislation and the increased interest in almost green products reduces the soil pollution by biodegradability which makes the manufacturing processes a clean process [6]. 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 [7]. Poor oxidative and hydrolytic stability, high temperature sensitivity of tribological behaviour and poor cold flow properties are the limitations of vegetable oils for lubricants [8]. 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.

Jacob *et al.* [9] developed a vegetable-based emulsion that can be used in the metal working industry, to replace partially or completely the commonly used petroleum based emulsions. Lawal *et al.* [10] evaluated the effect of vegetable and mineral oil-in-water emulsion cutting fluids in turning AISI 4340 steel with coated carbide tools on the surface roughness and cutting force. The study involved the selection of cutting fluid additives for the formulation of oil-in-water emulsion, using palm kernel and cottonseed oils. Similarly, Xavior and Adithan [11] studied the influence of cutting fluids on tool wear and surface roughness during turning of AISI 304 austenitic stainless steel. They identified the influence of coconut oil in reducing the tool wear and surface roughness during turning processes. Ojolo *et al*. [12] studied the effect of some straight biological oils (groundnut oil, coconut oil, palm kernel oil and shear butter oil) on cutting force when turning with round bars of three selected materials (mild steel, copper and aluminium) using tungsten carbide tool. The results obtained showed that bio-oils were suitable for metalworking fluids and that the effects of the bio-oils on cutting force, however, were material dependent. Belluco and De Chiffre [13] investigated the effects of new formulations of vegetable oils on surface integrity, part accuracy in reaming and tapping operations with AISI 316L stainless steel. Cutting fluid was found to have a significant effect on surface integrity and thickness of the strain hardened layer in the sub-surface, as well as part accuracy. Cutting fluids based on vegetable oils showed better performance than mineral oils. Cydas [14] studied the effect of dry cutting on surface roughness, tool flank wear and temperature during turning of AISI 4340 steel with ceramic tools. Suresh *et al.* [15] 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. Dhar *et al*. [16] evaluated tool wear and surface roughness under dry, wet (conventional) and MQL during turning of AISI 4340 steel with coated carbide tools. There are other studies on machining of AISI 4340 steel under dry cutting, however, only Avila and Abrao's [17] work investigated the effect of emulsion without mineral oil, emulsion synthetic, emulsion with mineral oil on tool wear, tool life, surface roughness and chip formation during turning of AISI 4340 steel with alumina tools. In this study, the effects of false walnut and groundnut oils based cutting fluids and commercial cutting fluid on surface roughness during turning of AISI 1330 alloy steel using high speed steel tool were investigated.

2. Materials and Method

2.1. Materials

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 was done using full factorial experimental method for each of the oils. The following additives were used:

1) emulsifier (polyoxyethylene sorbitan monostrate or Tween-80).
2) antioxidant (butylated hydroxytoluene-BHT).
3) corrosion Inhibitor (banana sap obtained from banana stem–*musa acuminate* plant [18].
4) 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).

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 30.1 HRC with the following composition percentages by weight: C (0.296), Si (0.461), Mn (1.230), Cr (0.060), Ni (0.022), Cu (0.080), W (0.011), P (0.040), S (0.023) and Fe (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. Method

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 [19]. 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 [20] [21]. 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 [20]-[22]. 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 2**. 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%.

2.2.2. Turning Conditions

The machining experiment involved the turning of the workpiece on a manually operated POTISJE PA 25 centre

Table 1. Characteristics of emulsion cutting fluids.

S/N	Properties	False 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

Table 2. 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

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. Surface roughness was chosen as an output parameter for evaluation, using the two vegetable oil-based cutting fluids and mineral oil- based cutting fluid. A portable surface roughness tester, model number CRV 135 used to measure the surface roughness (R_a) of the workpiece material after each experimental run. The surface roughness, (R_a), was taken using the surface roughness tester at three points on the workpiece. 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 3**. 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 surface roughness in this study.

3.1. Signal-to-Noise (S/N) Ratio Analysis

Table 4 shows the corresponding S/N (dB) ratio for the surface roughness. 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 surface roughness. 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 surface roughness.

The main effect plots for the surface roughness obtained from S/N ratio values of the machining parameters at different levels are shown in **Figure 1**. The plots indicated that the optimal machining parameters for the minimum surface roughness were obtained at cutting speed of 35 m/min (level 2), feed rate of 0.124 mm/rev (level 1), depth of cut of 0.3 mm (level 1) and a cutting fluid with a viscosity of 2.898 mm^2/s (level 3). Hence, the optimal parameters to obtain better surface finish of the workpiece were obtained when groundnut oil based cutting fluid was used. This may be as a result of the higher viscosity of the groundnut oil based cutting fluid.

3.2. Analysis of Variance for Surface Roughness

Analysis of variance (ANOVA) was used to determine the contribution of each parameter on the surface roughness as shown in **Table 5**. The contribution of each input parameter to the surface roughness was: cutting speed (6.82%), feed (46.42%), depth of cut (14.19%), and cutting fluid viscosity (14.22%) respectively. The results showed that the feed rate has the highest significance on the surface roughness, followed by the cutting fluid. This is in agreement with the study carried out by Noordin *et al.* [23], in which their finding showed that the surface roughness is dependent on the feed rate. The depth of cut ranked the third in influence, while the cutting speed had the least influence on the surface roughness.

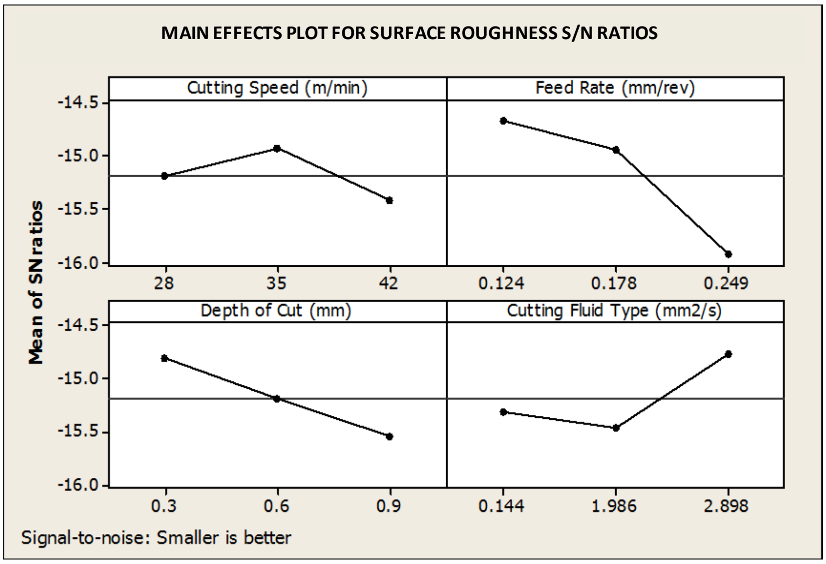

Figure 1. Main effects plot for surface roughness S/N ratios.

Table 3. 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 (mm^2/s)	Surface roughness (μm)
1	28	0.124	0.3	1.986	5.21
2	28	0.124	0.3	2.898	5.11
3	28	0.124	0.3	0.144	5.18
4	28	0.178	0.6	1.986	5.94
5	28	0.178	0.6	2.898	5.52
6	28	0.178	0.6	0.144	5.75
7	28	0.249	0.9	1.986	6.98
8	28	0.249	0.9	2.898	6.11
9	28	0.249	0.9	0.144	6.20
10	35	0.124	0.6	1.986	5.37
11	35	0.124	0.6	2.898	5.05
12	35	0.124	0.6	0.144	5.11
13	35	0.178	0.9	1.986	5.57
14	35	0.178	0.9	2.898	5.46
15	35	0.178	0.9	0.144	5.85
16	35	0.249	0.3	1.986	6.14
17	35	0.249	0.3	2.898	5.77
18	35	0.249	0.3	0.144	6.01
19	42	0.124	0.9	1.986	6.55
20	42	0.124	0.9	2.898	5.17
21	42	0.124	0.9	0.144	6.19
22	42	0.178	0.3	1.986	5.59
23	42	0.178	0.3	2.898	5.10
24	42	0.178	0.3	0.144	5.54
25	42	0.249	0.6	1.986	6.26
26	42	0.249	0.6	2.898	6.11
27	42	0.249	0.6	0.144	6.89

Table 4. Signal-to-noise ratio values for the responses.

Trial	Surface roughness (μm)	Signal-to-noise ratio for surface roughness (dB)
1	5.21	−14.3368
2	5.11	−14.16842
3	5.18	−14.2866
4	5.94	−15.4757
5	5.52	−14.8388
6	5.75	−15.1934
7	6.98	−16.8771
8	6.11	−15.7208
9	6.20	−15.8478
10	5.37	−14.5995
11	5.05	−14.0658
12	5.11	−14.1684
13	5.57	−14.9171
14	5.46	−14.7439
15	5.85	−15.3431
16	6.14	−15.7634
17	5.77	−15.2235
18	6.01	−15.5775
19	6.55	−16.3248
20	5.17	−14.2698
21	6.19	−15.8338
22	5.59	−14.9482
23	5.10	−14.1514
24	5.54	−14.8702
25	6.26	−15.9315
26	6.11	−15.7208
27	6.89	−16.7644

Table 5. Analysis of Variance for surface roughness.

Factor	DF	SS	MS	F-ratio	P %
Cutting speed (m/min)	2	0.525	0.262	3.3407	0.0682
Feed rate (mm/rev)	2	3.571	1.786	22.7731	0.4642
Depth of cut (mm)	2	1.092	0.546	6.9620	0.1419
Error	18	1.412	0.078		0.1835
Total	26	7.694			

3.3. Contour and Interation Plots of Surface Roughness

Contour plot in **Figure 2** shows the effect of cutting speed and feed rate on surface roughness. It is observed that, increase in cutting speed has very little effect on the surface roughness. For example, as the feed rate increased from 0.16 mm/rev to 0.18 mm/rev, the surface roughness increased from 5.2 - 5.6 μm to 5.6 - 6.0 μm, whereas,

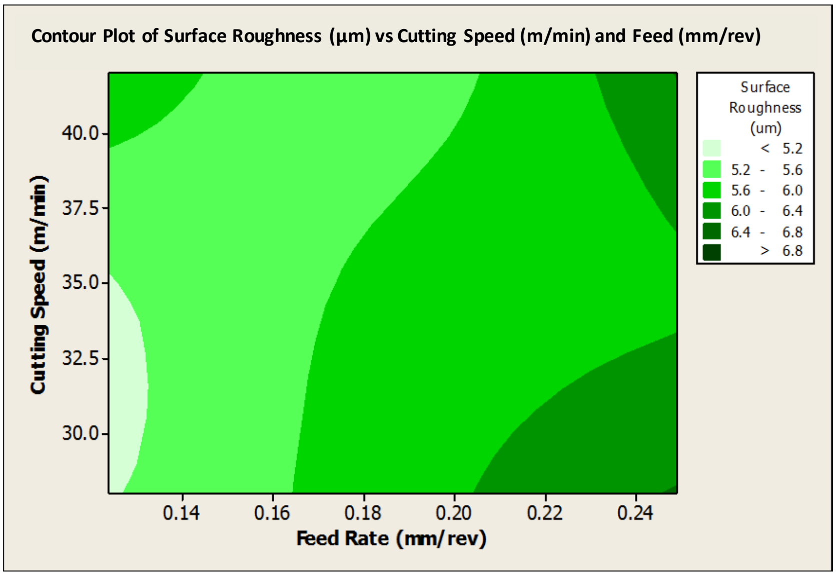

Figure 2. Contour plot of Surface roughness versus cutting speed and feed.

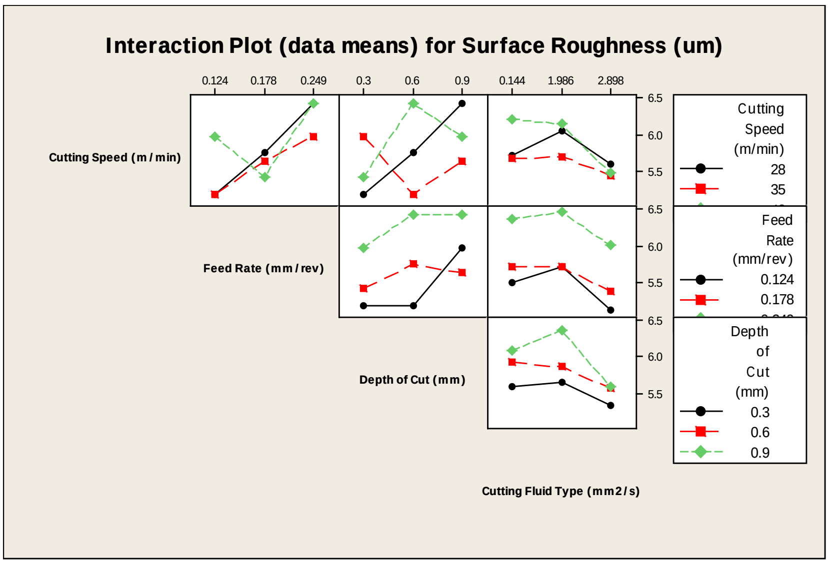

Figure 3. Interaction plot for surface roughness.

increase in cutting speed from 30 m/min to 32.5 m/min had little or no effect on the surface roughness.

In **Figure 3**, there are interactions between the three cutting speeds and the three feed rates. The cutting speed of 28 m/min interacted with cutting speed of 35 m/min at the feed rate of 0.124 mm/rev, and with the cutting speed of 42 m/min at feed rates of 0.16 and 0.249 mm/rev respectively. On the other hand, the cutting speeds of 35 and 42 m/min interacted at feed rates of 0.165 and 0.185 mm/rev respectively. In the same vein, there is interaction between cutting speed and depth of cut. It is observed that the cutting speed of 28 m/min interacted with that of 35 and 42 m/min, at depths of cuts of 0.5 and 0.8 mm respectively

Also, the cutting speeds of 35 and 42 m/min interacted with each other at depths of cut of 0.4 mm only. While the interaction between feed rate and depth of cut showed that only the feed rates of 0.124 and 0.178 mm/rev interacted at depth of cut of 0.8 mm. The feed rate of 0.249 mm/rev did not interact with any other feed rate. The interaction between cutting speed and cutting fluid type showed that the cutting speeds of 28 and 42 m/min interacted at cutting fluid viscosity of about 0.23 mm^2/s. Also, the cutting speeds of 28 and 35 m/min interacted at cutting fluid viscosity of 0.144 mm^2/s. It was also observed that the cutting speeds of 35 and 42 m/min did not interact with any other parameters. For feed rate and cutting fluid types, only the feed rates of 0.124 and 0.178 mm/rev interacted at cutting fluid viscosity of 1.986 mm^2/s. The feed rate of 0.249 mm/rev did not interact with any other feed rate. It was observed that only the depth of cuts of 0.6 and 0.9 mm interacted at the cutting fluid viscosity of 2.898 mm^2/s. The depth of cut of 0.3 mm did not interact with any other depth of cut.

4. Conclusion

Experiments involving high speed steel tools and AISI 1330 alloy steel under varying machining conditions and cutting fluids were conducted. These were done using L_{27} (3^4) orthogonal array and each experiment was repeated three times. Each test used a new cutting tool to ensure accurate readings of the surface roughness. Experimental results were analyzed using signal-to-noise ratio and ANOVA. Results showed optimal machining parameters for obtaining minimum surface roughness at cutting speed of 35 m/min (level 2), feed of 0.124 mm/rev (level 1), depth of cut of 0.3 mm (level 1) and a cutting fluid with a viscosity of 2.898 mm^2/s (level 3). Analysis of variance shows that feed rate (46.42%) has the significant influence on surface roughness, followed by the type of cutting fluid, in this case groundnut oil based cutting fluid with 14.22% significant.

References

[1] Abu, J.O. (2011) Manufacturing Engineering and Production Management. Aboki Publishers, Makurdi, 275-287.

[2] Abu, J.O. (2011) Manufacturing Engineering and Production Management. Aboki Publishers, Makurdi, 289-291.

[3] Alander, J. and Warnhein, T. (1989) Model Microemulsions Containing Vegetable-Oils 1, NONIONIC Surfactanct systems. *Journal of the American Oil Chemists Society*, **66**, 1656-1660. http://dx.doi.org/10.1007/BF02636197

[4] Lawal, S.A., Choudhury I.A. and Nukman, Y. (2012) Application of Vegetable Oil-Based Cutting Fluids in Machining Ferrous Metals—A Review. *International Journal of Machine Tools & Manufacturing*, **52**, 1-12. http://dx.doi.org/10.1016/j.ijmachtools.2011.09.003

[5] Cetin, M.H., Ozcelik, B., Kuram, E. and Demirbas, E. (2011) Evaluation of Vegetable Based Cutting Fluids with Extreme Pressure and Cutting Parameters in Turning of AISI 304L by Taguchi Method. *Journal of Cleaner Production*, **19**, 2049-2056. http://dx.doi.org/10.1016/j.jclepro.2011.07.013

[6] Alves, S.M. and Oliveira, J.F.G. (2006) Development of New Cutting Fluid for Grinding Process Adjusting Mechanical Performance and Environmental Impact. *Journal of Materials Processing Technology*, **179**, 185-189. http://dx.doi.org/10.1016/j.jmatprotec.2006.03.090

[7] Adhvaryu, A. and Erhan, S.Z. (2002) Epoxidized Soybean Oil as a Potential Source of High Temperature Lubricants. *Industrial Crops Production*, **15**, 247-254. http://dx.doi.org/10.1016/S0926-6690(01)00120-0

[8] Erhan, S.Z. and Asadauskas, S. (2000) Lubricant Base Stocks from Vegetable oils. *Industrial Crops Production*, **11**, 277-282. http://dx.doi.org/10.1016/S0926-6690(99)00061-8

[9] Jacob, J., Bhattacharya, M. and Raynor, P.C. (2004) Emulsions Containing Vegetable Oils for Cutting Fluid Application. *Colloids and surface A: Physiochemical Engineering Aspects*, **237**, 141-150. http://dx.doi.org/10.1016/j.colsurfa.2003.12.029

[10] Lawal, S.A., Choudhury I.A. and Nukman, Y. (2014) Evaluation of Vegetable and Mineral Oil-in-Water Emulsion Cutting Fluids in Turning AISI 4340 Steel with Coated Carbide Tools. *Journal of Cleaner Production*, **66**, 610-618. http://dx.doi.org/10.1016/j.jclepro.2013.11.066

[11] Xavior, M.A. and Adithan, M. (2009) Determining the Influence of Cutting Fluids on Tool Wear and Surface Roughness during Turning of AISI 304 Austentic Stainless Steel. *Journal of Material Processing Technology*, **20**, 900-909. http://dx.doi.org/10.1016/j.jmatprotec.2008.02.068

[12] Ojolo, S.J., Amuda, M.O.H., Ogunmola, O.Y. and Ononiwu, C.U. (2008) Experimental Determination of the Effect of Some Straight Biological Oils on Cutting Force during Cylindrical Turning. *Matérial*, **13**, 650-663. http://dx.doi.org/10.1590/s1517-70762008000400011

[13] Belluco, W. and De Chiffre, L. (2004) Performance Evaluation of Vegetable-Based Oils in Drilling Austenitic Stainless Steel. *Journal of Material Processing Technology*, **148**, 171-176. http://dx.doi.org/10.1016/S0924-0136(03)00679-4

[14] Cydas, U. (2010) Machinability Evaluation in Hard Turning of AISI 4340 Steel with Different Cutting Tools Using Statistical Technique. *Proceeding of Institution of Mechanical Engineering Part B*: *Journal of Engineering Manufacture*, **224**, 1043-1055. http://dx.doi.org/10.1243/09544054JEM1822

[15] Suresh, R., Basavarajappa, S. and Samuel, G.L. (2012) Some Studies on Hard Turning of AISI 4340 Steel Using Multilayer Coated Carbide Tool. *Measurement*, **45**, 1872-1884. http://dx.doi.org/10.1016/j.measurement.2012.03.024

[16] Dhar, N.R., Kamruzzaman, M. and Ahmed, M. (2006) Effect of Minimum Quantity Lubrication (MQL) on Tool Wear and Surface Roughness in Turning AISI 4340 Steel. *Journal of Materials Processing Technology*, **172**, 299-304. http://dx.doi.org/10.1016/j.jmatprotec.2005.09.022

[17] Avila, R.F. and Abrao, A.M. (2001) The Effect of Cutting Fluids on the Machining of Hardened AISI 4340 Steel. *Journal of Material Processing Technology*, **119**, 21-26. http://dx.doi.org/10.1016/S0924-0136(01)00891-3

[18] El-Sayed, M., Mansour, O.Y., Selim, I.Z. and Ibrahim, M.M. (2001) Identification and Utilization of Banana Plant Juice and Its Pulping Liquor as Anti-Corrosive Materials. *Journal of Scientific & Industrial Research*, **60**, 738-747.

[19] Sanyılmaz, M. (2006) Design of Experiment and an Application for Taguchi Method in Quality Improvement Activity. M.S. Thesis, Dumlupınar University, Kütahya.

[20] Aslan, E., Camuscu, N. and Bingoren, B. (2007) Design Optimization of Cutting Parameters When Turning Hardened AISI 4140 (63 HRC) with Al_2O_3 + TiCN Mixed Ceramic Tool. *Materials & Design*, **28**, 1618-1622.

[21] Ghani, J.A., Choudhury, I.A. and Hassan, H.H. (2004) Application of Taguchi Method in the Optimization of End Milling Operations. *Journal of Material Processing Technology*, **145**, 84-92. http://dx.doi.org/10.1016/S0924-0136(03)00865-3

[22] Park, S.H. (1996) Robust Design and Analysis for Quality Engineering. Chapman and Hall, London.

[23] Noordin, M.Y., Venkatesh, V.C., Chan, C.L. and Abdullah, A. (2001) Performance Evaluation of Cemented Carbide Tools in Turning AISI 1010 Steel. *Journal of Materials Processing Technology*, **116**, 16-21.