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Procedia Materials Science 5 (2014) 1966 – 1975

Procedia Materials Science

www.elsevier.com/locate/procedia

International Conference on Advances in Manufacturing and Materials Engineering, AMME 2014

Comparative evaluations of surface roughness during hard turning under dry and with water-based and vegetable oil-based cutting fluids

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Abstract

In this work, an experimental investigation through mathematical modeling was carried out to study the effects of different cooling mediums and cutting parameters on surface roughness during turning of hardened AISI 52100 steel (60-62 HRC). Experiments were performed using PVD-coated nanolaminated TiSiN-TiAlN carbide tool under dry, with water-based and coconut oil-based cutting fluids. Experimental observations indicate that hard turning under dry condition produced lower values of surface roughness. However, at higher cutting speeds hard turning using coconut oil showed lower values of surface roughness. The coconut oil also found to be more effective in lowering surface roughness at higher values of feed and depth of cut. It has been observed that the surface roughness gets affected mostly by feed and increased when cutting speed exceeds 150-160 m/min irrespective of the cooling mediums used. However, this effect can be seen as more prominent when turning under dry cutting conditions.

Selection and peer-review under responsibility of Organizing Committee of AMME 2014

Keywords: Hard turning; Surface roughness; Cooling mediums; Coated carbide tool; Vegetable oil; Response surface methodology.

1. Introduction

Among users, machining of extremely tough and hard steels using most economical cutting tool materials are continuously increasing. A group of researchers (Noordin et al., 2007; Avila et al., 2008; Chinchanikar and

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Selection and peer-review under responsibility of Organizing Committee of AMME 2014
doi:10.1016/j.mspro.2014.07.529

Choudhury, (2013); Chinchanikar et al.,(2013) attempted machining of hardened steel using coated carbide tools. However, in most of the studies workpiece hardness was limited to 50 HRC.

With continuous developments in new coating materials and particularly, with nanostructure and nanocomposite coatings, coated carbide tools can become an economical alternative to costly PCBN and ceramic inserts which are commonly preferred to machine the hardened workpiece having hardness greater than 50 HRC. Most of the researchers performed machining of the hardened steel under dry cutting as increase in temperature during the process makes chip deformation and shearing of the hardened material easier Dogra et al., (2012); Lima et al., (2007); Kurniwan et al., (2010). Moreover, it is reported that at higher cutting speeds, most of the heat is carried away along with the chip making the use of cutting fluid redundant. However, cutting fluids play a significant role in machining areas. The complete absence of cutting fluid creates problems in chip transportation and causes an increase of the tool-chip and tool-workpiece friction affecting the tool life and quality of the machined surface. Moreover, the proper application of cutting fluid or cooling medium allows use of higher cutting speeds and higher feed rates by limiting overheating of the cutting tool and machine.

Although, cutting fluids are beneficial in the industries, today their uses have become more and more prevalent around the world due to environment consciousness enhanced laws and regulations Diniz et al., (2003). Cutting fluids are contaminated with metal particles and degradation products which create health and environmental issues. From last decade, green machining including dry cutting, minimum quantity lubrication (MQL), compressed air cooling, liquid nitrogen cooling and uses of vegetable oil as cutting fluids; since they are environmentally friendly, have been mostly attempted by the researchers during machining Shokrani et al., (2012). Vegetable oils are getting more and more attention in industry as metal working fluids as they are renewable, biodegradable, non toxic and have high viscosity and high flash point Maleque et al.,(2003). Among users, vegetable-based oils, especially, rapeseed Belluco and De Chiffre,(2004), canola Lawal et al.,(2012), and coconut oil Xavior and Adithan,(2009); Jayadas et al.,(2007); Krishna et al.,(2010) are mostly preferred as cutting fluids and become effective substitutes to mineral oil-based lubricants. It is reported that the use of vegetable oil as cutting fluid alleviates problems faced by workers such as skin cancer and inhalation of toxic mists in the working environment (John et al., 2004).

Khan and Dhar (2006) investigated the effect of MQL using vegetable oil on cutting temperature, tool wear, surface roughness and dimensional deviation in turning of AISI 1060 steel. They observed that using MQL the cutting temperature, cutting forces, tool wear and surface roughness reduced significantly in comparison to values obtained under dry machining. Ozcelik et al. (2011) experimental study during turning of AISI 304L stainless steel using sunflower oil, canola oil, semi-synthetic and mineral-based oils as cutting fluids concluded that mineral and semi-synthetic cutting fluids could be replaced by vegetable-based oils. Bruni et al. (2006) employed MQL system using a very low quantity of vegetable oil (10 ml/h) mixed with air. They observed that MQL technique did not significantly reduce the tool wear, whilst wet cutting produced the worst surface finish.

Ojolo et al. (2008) performed turning of mild steel, aluminum and copper using vegetable-based oils, namely, groundnut oil, coconut oil, palm kernel oil and shear butter oil. They found that the performance of vegetable-based cutting fluids depend on the workpiece material and cutting parameters employed during machining. They observed better performance with groundnut oil. Xavior and Adithan (2009) compared the performance of coconut oil, emulsion and neat cutting oils during turning of AISI 304 stainless steel. They found lower tool wear and improved surface finish with coconut oil. In another study, they observed that coconut oil outperformed the soluble and straight cutting oils in terms of reducing the cutting force and temperature. Avila and Abrao (2001) found that emulsion-based fluid (without mineral oil) and dry cutting provide better results followed by synthetic fluid and emulsion containing mineral oil during turning of hardened AISI 4340 steel (49 HRC) using mixed alumina inserts.

From the literature reviewed, it has been observed that very few studies are reported on using coolants in hard turning while most works do without it. Moreover, there is disagreement between the researchers about the use of coolants in hard turning, which needs further investigations. With this view, in this study, turning experiments which were designed using statistical techniques are performed to study the effects of cutting parameters and different cooling mediums, namely, water-based and vegetable oil-based cutting fluids on the surface roughness and its comparison when turning under dry condition to address the widely debated topic on the application of coolant in hard turning. Mathematical models to predict surface roughness for each case are developed based on experimental results obtained in wide range of cutting conditions during turning of hardened AISI 52100 steel (60-62 HRC) with PVD-coated nanolaminated TiSiN-TiAlN carbide tool.

2. Experimental details

2.1. Cutting inserts and experimental procedure

Turning tests were performed on hardened AISI 52100 steel (60-62 HRC) which were carried out on a CNC lathe (Model: Simple Turn-5075, Ace Micromatic, India, and Controller: Simens-802C). Workpiece hardness was maintained uniform throughout the cross section with a maximum variation of ± 2 HRC by a precisely controlled hardening and tempering process. The workpiece used has a length and diameter of 600 and 60 mm, respectively. Experiments were performed using PVD-coated nanolaminated TiSiN-TiAlN carbide inserts (ISO class P10) (http://www.secotools.com, 2014). All the insets have identical geometry designated by ISO as CNMG 120408 (80^0 diamond shape with 0.8 mm nose radius) with integral chip breaker geometry of type MF2. A right hand style tool holder designated by ISO as PCLNR 2525M12 was used for mounting the inserts.

During experiments, workpiece was held in a three jaw chuck and supported by a center in the tailstock. Tool height, its overhang and tool geometry were kept constant. Tool height and its overhang were set to the required level with the help of gauges. Before carrying out actual experiments, some rough turning pass was made in order to completely remove the surface irregularities and oxidized layer from the workpiece surface. Surface roughness values were measured by a Surtronics DUO surface roughness tester (Taylor and Hobson make) with a least count of 0.1μm. It gives direct digital value of R_a. Instrument was calibrated by using standard specimen provided by the manufacturer. For surface measurement, the instrument was held on the machined surface. The stylus of the traversing unit measured the surface roughness by traversing through a fixed sample length. Surface roughness was measured at different points on the machined surface, and the average surface roughness value was noted.

2.2 Cooling mediums

In this study, turning experiments were carried out under dry condition and with different cooling mediums, namely, water-based and vegetable oil-based cutting fluids. Coconut oil (vegetable oil) and Servocut S, water-based cutting oil was used as cutting fluids. Servocut S is a soluble type high quality cutting oil, which yields rich milky emulsion with water. This oil contains rust inhibitors, which impart anti-rust and anti-corrosive properties to the emulsion. To obtain stable emulsion, oil was added to water as recommended by the oil manufacturer. A homogeneous dispersion of oil in water was obtained by continuous stirring while preparing the emulsion. The ratio of oil to water was kept 1:20, (5% concentration of oil in water). The flow rate for both the cutting fluids was kept constant to a value of l l/hr for all the experiments.

2.3 Cutting conditions

Experiments were planned using central composite rotatable design (CCRD) matrix varying the cutting speed, feed and depth of cut [24]. Ranges of cutting parameters were decided on the basis of machine capability, literature review and tool manufacturer's recommendation. In this study, 20 experiments were performed for each cooling medium to develop a surface roughness model. Coded levels and corresponding actual values of cutting parameters are given in Table 1.

Table 1. Coded levels and corresponding actual values of cutting parameters.

Parameters	Levels				
	- 1.6817	- 1	0	+ 1	+ 1.6817
Cutting speed (V) (m/min)	100	125	150	175	200
Feed (f) (mm/rev)	0.1	0.15	0.2	0.25	0.3
Depth of cut (d) (mm)	0.1	0.2	0.3	0.4	0.5

3. Mathematical models

3.1. Regression equations

Turning experiments were performed varying the cutting speed, feed and depth of cut as depicted in Table 1. For each of the experiment a fresh cutting insert was used. After each experiment surface roughness was measured at different points on the machined surface, and the average value was noted. Analysis of the experimental results was performed using standard Response Surface Methodology (RSM) technique. Regression equations for surface roughness (R_a) were developed based on experimental data. The values of the coefficients involved in the equation were calculated by regression method by using Stat-Ease Design Expert® software. Equations developed for surface roughness for dry and with water-based and coconut oil-based cutting fluids in terms of actual factors are given below:

Surface roughness: Dry condition,

$$R_a = +7.6011 - 0.0616\,V - 22.6977\,f - 7.2147\,d + 0.05\,V\,f + 0.008\,V\,d + 12.5\,f\,d + 0.0001\,V^2 + 41.1818\,f^2 + 8.6704\,d^2 \tag{1}$$

Surface roughness: Water-based cutting fluid,

$$R_a = +4.1237 - 0.0418\,V - 5.95\,f - 2.6125\,d + 0.01\,V\,f + 0.002\,V\,d - 4\,f\,d + 0.0001\,V^2 + 25\,f^2 + 7.5\,d^2 \tag{2}$$

Surface roughness: Coconut oil-based cutting fluid,

$$R_a = +5.065 - 0.0443\,V - 14.25\,f - 0.27\,d + 0.02\,V\,f - 0.034\,V\,d + 13\,f\,d + 0.0001\,V^2 + 30\,f^2 + 5.75\,d^2 \tag{3}$$

3.2. Adequacies of the developed models

The adequacies of the developed equations were checked by Analysis of Variance (ANOVA) technique. R-Squared (R^2) is a correlation coefficient, which measures variation proportion in the data points, ranging from -1 to +1. The value of R close to +1 indicates that the equation is significant. On the other hand, the Adjusted R-Squared which is a measure of the amount of variation about the mean and the Predicted R-Squared which is a measure of how good the model predicts a response value should be within about 0.20 of each other. Otherwise, there may be a problem with either the data or the model. Adequate precision or a signal-to-noise ratio value which is a measure of the range in predicted response about its associated error should be 4 or more. ANOVA results for surface roughness models are depicted in Table 2. It can be seen that the values of R-Squared for all the developed equations (Eqns. (1) to (3)) are close to 1 and the Adjusted and Predicted R-Squared values are in reasonable agreement. Adequate precision values are more than 4; therefore the equations obtained are significant. The model F-value obtained for all the equations also implies that the model is significant.

Table 2. ANOVA results for surface roughness models.

Factors	Different cooling mediums		
	Dry	*Water-based cutting fluid*	*Coconut oil-based cutting fluid*
R-squared	0.973	0.9668	0.9768
Adj. R-Squared	0.9488	0.9369	0.956
Pred. R-Squared	0.8263	0.8212	0.8381
Adeq. Precision	19.03	17.782	22.758
Model F-value	40.09	32.35	46.85

If the values of ‘Prob > F’ is less than significance level then it indicates that the model is significant. The significance level for a given hypothesis test is a value for which a p-value less than or equal to significance level is considered statistically significant (Montgomery, 2001). In the present study, significance level was taken as 0.05. Values greater than 0.05 indicate that the model terms are not significant. ANOVA results for F-values of surface roughness are shown in Table 3. The factors which were having significant effect on surface roughness are shown by underlining the F-value. Similarly, percentage contributions of different elements, obtained by dividing the corresponding element F-value with the total F-value, are also shown in Table 3. It can be seen that surface roughness get affected mostly by feed value (nearly 40-60% contribution) followed by depth of cut (nearly 20% contribution) with cutting speed having little influence. However, higher order of cutting speed can be seen as having significant effect on surface roughness. It can be seen that some of the elements in an interaction effects and elements with their higher orders appeared to be significant model terms when using different cooling mediums. Percentage contributions of these significant model terms are shown in bold-case. Although, these elements (elements in an interaction effects and elements with their higher orders) provided secondary contributions to different responses, their contributions can be seen as less prominent in comparison to contributions of feed value.

Table 3. ANOVA results for F-values showing percentage contribution of different parameters on surface roughness.

Elements	*Dry*		*Water-based cutting fluid*		*Coconut oil-based cutting fluid*	
	F-value	% Contribution	F-value	% Contribution	F-value	% Contribution
V	30.16[*]	**7.59**[*]	5.34	**1.68**	5.05	**1.09**
f	161	**40.56**	158.09	**49.91**	258.95	**56.16**
d	72.62	**18.29**	64.33	**20.31**	21.82	**4.73**
Vf	4.98	1.25	0.26	0.08	1.49	0.32
Vd	0.51	0.12	0.04	0.01	17.30	**3.75**
fd	4.98	**1.25**	0.66	0.21	10.11	**2.19**
V^2	50	**12.6**	37.94	**11.97**	79.08	**17.15**
f^2	42.48	**10.7**	20.51	**6.47**	42.34	**9.18**
d^2	30.12	**7.59**	29.54	**9.32**	24.88	**5.39**
Total	396.88	100	316.75	100	461.08	100

[*] Factors having significant effect on surface roughness are shown by underlining the F-value and their percentage contribution in bold-case.

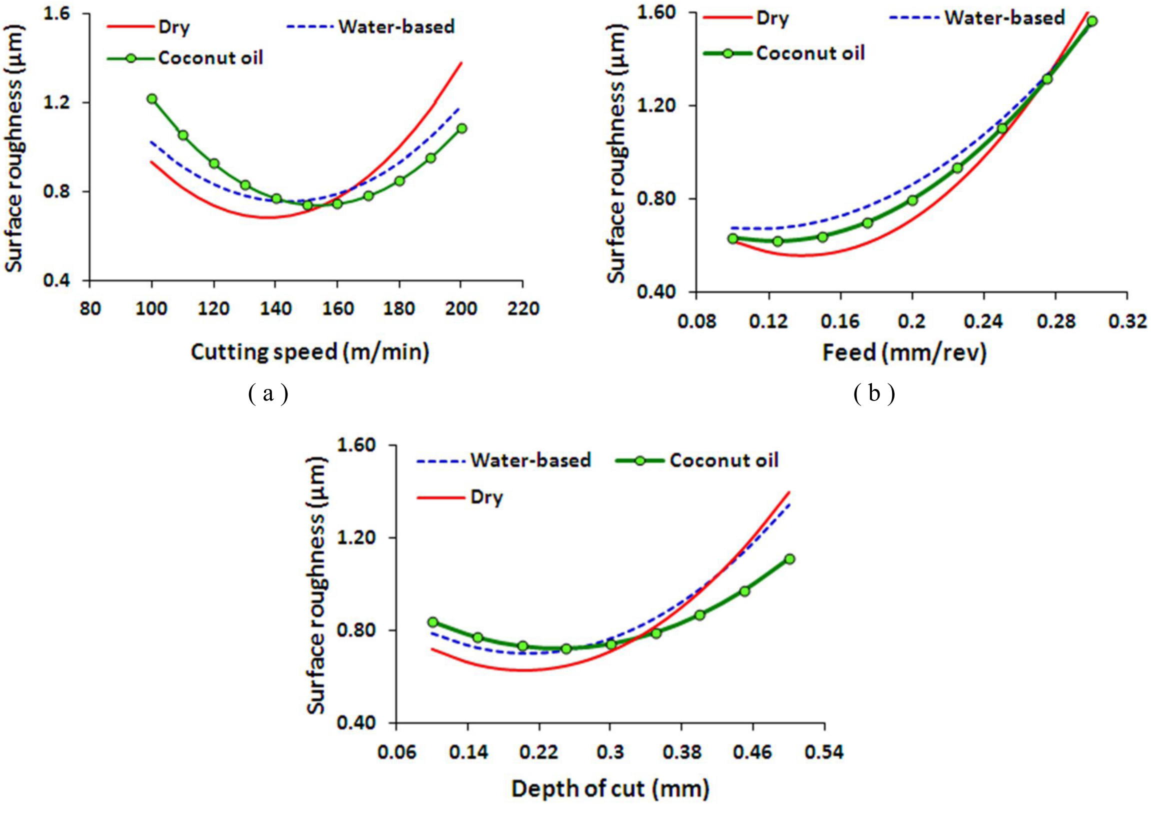
4. Results and discussion

In this section, effect of different cooling mediums and cutting parameters on surface roughness during turning of hardened AISI 52100 steel (60-62 HRC) using PVD-coated nanolaminated TiSiN-TiAlN carbide inserts is discussed based on the developed regression equations. Curves showing the various responses are plotted by varying one of the input parameters and keeping the other parameters constant. 3-D response surface plots are aso plotted to show the interaction effects of cutting parameters on various responses.

4.1 Effect of cutting parameters on surface roughness

Curves showing the surface roughness are plotted by varying one of the input parameters and keeping the other parameters constant. Fig. 1(a) depicts the variation of surface roughness with cutting speed, plotted using feed value of 0.2 mm/rev and depth of cut of 0.3 mm, obtained under dry and with water-based and coconut oil cutting fluids. It can be seen that the surface roughness produced is higher when using water-based cutting fluid and is lower when turning under dry cutting condition. However, increase in surface roughness values exceeding the values obtained when using water-based and coconut oil-based cutting fluids can be seen for dry cutting at higher cutting speeds. Decrease in surface roughness can be seen with the increase in cutting speed. However, surface roughness increased when cutting speed exceeds 150-160 m/min irrespective of the cooling mediums used. This may be because of change in frictional conditions and failure of the tool nose due to increased tool wear at higher cutting speeds. However, this effect can be seen as more prominent when turning under dry cutting conditions. Variation of surface roughness with respect to feed and depth of cut are shown in Figs. 1(b) and (c). It can be seen that surface roughness vary almost linearly with feed and depth of cut which is in line with the classical theory of metal machining. However, feed value can be seen as having most significant effect on the surface roughness.

From Figs. 1(a)-(c), it can be seen that hard turning with vegetable oil; coconut oil-based cutting fluid produce better surface finish at higher cutting parameters in comparison to dry cutting and with water-based cutting fluid. However, at lower cutting speed range of 100-150 m/min and lower values of depth of cut in the range of 0.1 to 0.3 mm, hard turning under dry cutting condition is the better option to obtain better surface finish.



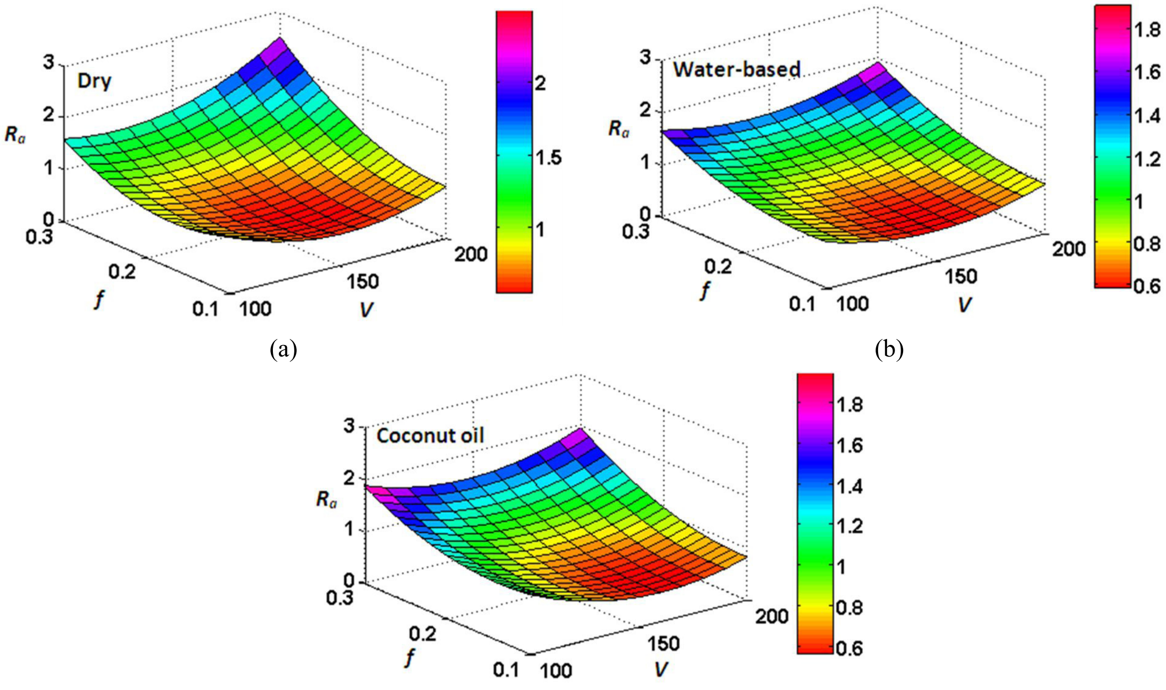
(a) (b)

(c)

Fig. 1. Effect on surface roughness by (a) Cutting sped; (b) Feed; (c) Depth of cut.

4.2 3-D response surfaces showing interaction effects

In order to have the clear understanding of the effect of a given input parameter on the surface roughness, when hard turning under dry cutting conditions and with water-based and coconut oil-based cutting fluids using PVD-coated nanolaminated TiSiN-TiAlN carbide tool, 3-D response surfaces are plotted with varying two of the input parameters and considering value of one of the input parameters at centre point (Table 1) as shown in Figs. 2-4. 3-D response surfaces of surface roughness for dry cutting and with water-based and coconut oil-based cutting fluids are plotted using the developed models of surface roughness as discussed in Section 3.1. Fig. 2 depicts the 3-D response surfaces showing interaction effects of cutting speed and feed on surface roughness when hard turning under dry cutting conditions and with water-based and coconut oil-based cutting fluids, which are plotted using Eqns. (1) to (3), respectively.



(a)

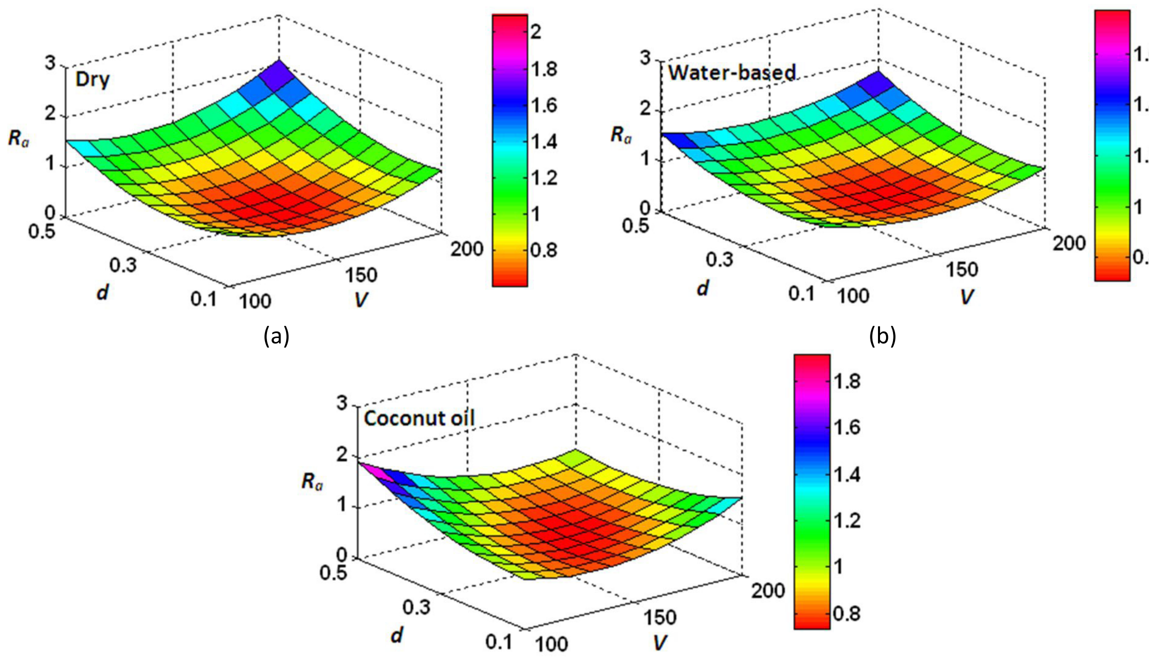
(b)

(c)

Fig. 2. 3-D response surfaces showing interaction effects of cutting speed and feed on surface roughness for (a) Dry; (b) Water-based; (c) Coconut oil-based cutting fluids.

During hard turning under dry condition, terms *V* x *f* and *f* x *d* have an interaction effects on surface roughness as depicted in Table 3, which can be clearly seen from Figs. 2(a) and 4(a), respectively. From Fig. 2(a), it can be seen that increase in the surface roughness with feed value is more prominent at higher cutting speeds for dry cutting in comparison to increase in the surface roughness with feed value at lower cutting speeds. Howecer, when using water-based and vegetable oil-based cutting fluids, more or less uniform increase in the surface roughness can be seen with the increase in value of feed for the range of cutting speed considered in the present study, i.e., there is no interaction effect of *V* x *f* on surface roughness (Figs. 2(b) and (c)).

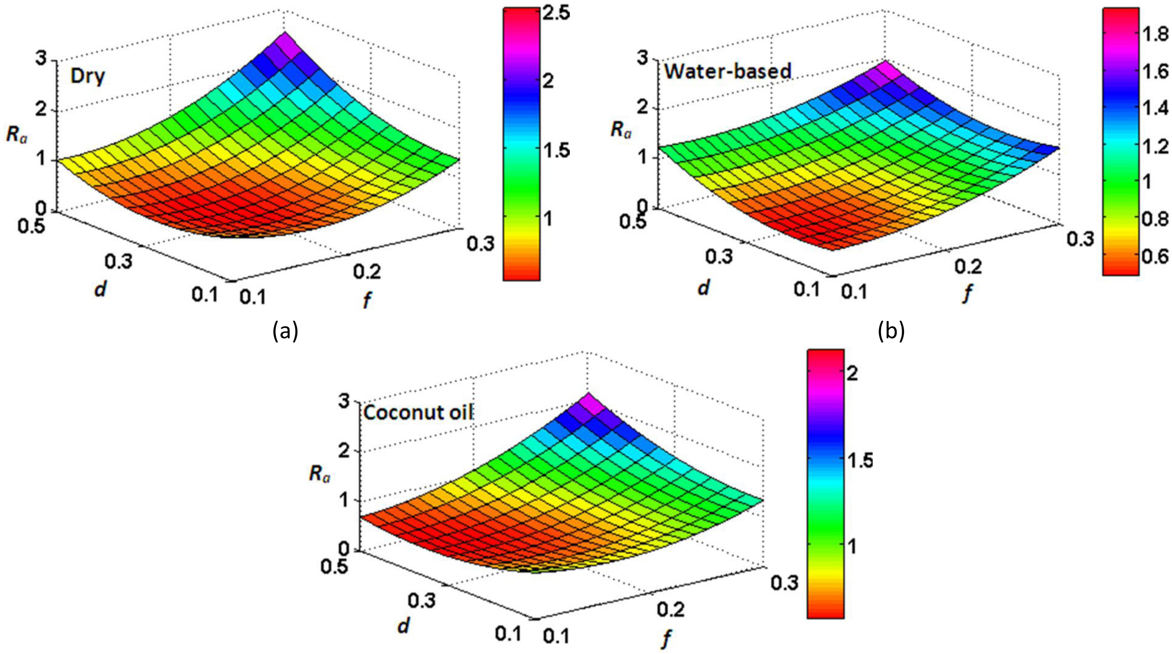
On the other hand, from Figs. 4(a) and (c), it can be seen that the increase in the surface roughness with depth of cut is more prominent at higher feed values in comparison to lower value of feed, i.e., interaction effect of *f* x *d* appeared to be significant on surface roughness for dry cutting and when using coconut oil-based cutting fluid. However, this effect can be seen as less prominent for hard turning when using water-based cutting fluid as shown in Fig. 4(b). Similarly, interaction effect of term *V* x *d* on surface roughness when hard turning under dry cutting conditions and with water-based and coconut oil-based cutting fluids are shown in Figs. 3(a)-(c). It can be seen that interaction effect of *V* x *d* appeared to be significant on surface roughness when using coconut oil-based cutting fluid. Fig. 3(c) revels that at lower cutting speeds, surface roughness increases sharply with increase in depth of cut. However, it can be seen that higher cutting speed coupled with higher depth of cut significantly reduces the surface roughness when using coconut oil-based cutting fluid during hard turning (Fig. 3(c)).



(a) (b)

(c)

Fig. 3. 3-D Response surfaces showing interaction effects of cutting speed and depth of cut on surface roughness for (a) Dry; (b) Water-based; (c) Coconut oil-based cutting fluids.



(a) (b)

(c)

Fig. 4. 3-D response surfaces showing interaction effects of feed and depth of cut on surface roughness for (a) Dry; (b) Water-based; (c) Coconut oil-based cutting fluids.

From 3-D response surfaces (Figs. (2)-(4)), it can be seen that surface roughness increases with increase in the values of feed, depth of cut and beyond the cutting speed of 150-160 m/min. It can be seen that the coconut oil-based cutting fluid produced lower values of surface roughness, especially at higher values of cutting parameters in comparison to hard turning under dry and with water-based cutting fluid. However, by limiting the cutting parameters, especially cutting speed up-to 150 m/min, hard turning under dry condition can be seen as the better option to obtain lower values of surface roughness. Further, cutting conditions were optimized to obtain minimum value of surface roughness using in-built module of Design Expert software. The ranges of cutting parameters were selected as depicted in Table 1. Optimum cutting conditions found for minimum surface roughness for hard turning under dry and with water-based and coconut oil-based cutting fluids are given in Table 4.

Table 4. Optimum cutting conditions for minimum surface roughness during hard turning under dry and with different cooling mediums.

Optimum conditions for dry and different cooling mediums		Cutting speed (V) (m/min)	Feed (f) (mm/rev)	Depth of cut (d) (mm)	Surface roughness R_a (μm)	Desirability
Dry cutting	D1	146.44	0.15	0.24	0.5248	1
	D2	144.57	0.16	0.22	0.5356	1
	D3	144.37	0.15	0.26	0.5364	1
Water-based cutting fluid (WB)	WB1	147.19	0.15	0.21	0.5309	1
	WB2	144.65	0.15	0.2	0.53	1
	WB3	135.86	0.15	0.24	0.5575	0.9813
Coconut oil-based cutting fluid (CO)	CO1	162.29	0.15	0.32	0.5779	1
	CO1	158.76	0.15	0.33	0.5782	1
	CO1	167.64	0.15	0.32	0.5898	0.9888

It can be seen that the surface roughness in the range of 0.5-0.6 μm; comparable to values obtained using grinding operation, could be achieved during hard turning of AISI 52100 steel (60-62 HRC) with PVD-coated nanolaminated TiSiN-TiAlN carbide tool. Further, it can be seen that almost similar values of surface roughness produced during hard turning under dry condition and with water-based and coconut oil-based cutting fluids. However, using coconut oil-based cutting fluid, better surface finish could be obtained by employing higher values of cutting parameters in comparison to hard tuning under dry and with water-based cutting fluid. Although, application of cutting fluids not improved the surface finish as such in comparison to dry cutting, use of cutting fluids may influence the cutting forces and the tool life. Hence, another study will be taken-up to investigate the effect of different cooling mediums on machining performance in terms of cutting forces and tool life during hard turning.

5. Conclusions

Hard turning experiments under dry and with water-based and coconut oil-based cutting fluids were performed on hardened AISI 52100 steel (60-62 HRC) using PVD-coated nanolaminated TiSiN-TiAlN carbide tool. Comparative evaluations of surface roughness produced were made considering the effect of different cooling mediums and cutting parameters through mathematical modeling using response surface methodology. Highly significant parameters on surface roughness were determined by performing an Analysis of variance (ANOVA). Experimental observations indicate that hard turning with cutting fluids not significantly improved the surface finish in comparison to dry cutting. However, coconut oil-based cutting fluid produced lower values of surface roughness, especially at higher values of cutting parameters in comparison to hard turning under dry and with water-based cutting fluid. Surface roughness, although, initially decreased with increase in cutting speed observed to be increased when cutting speed exceeds 150-160 m/min irrespective of the cooling mediums used. It has been observed that the surface roughness gets affected mostly by feed followed by depth of cut. However, this effect has been observed to be more prominent in case of hard turning under dry condition. In the present study, the surface roughness in the range of 0.5-0.6 μm obtained is comparable to the values obtained using grinding operation. However, it has been observed that by limiting the cutting parameters, especially cutting speed up-to 150 m/min, hard turning under dry condition could be the better option in comparison to hard turning with cutting fluids. However, use of cutting fluids may influence the cutting forces and the tool life and hence, another study is required to investigate the effect of different cooling mediums on machining performance in terms of cutting forces and tool life during hard turning.

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