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Investigation of the influential parameters of machining of AISI 304 stainless steel

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Abstract. Austenitic stainless steels are hard materials to machine, due to their high strength, high ductility and low thermal conductivity. The last characteristic results in heat concentration at the tool cutting edge. This paper aims to optimize turning parameters of AISI 304 stainless steel. Turning tests have been performed in three different feed rates (0.2, 0.3, 0.4 mm/rev) at the cutting speeds of 100, 125, 150, 175 and 200 m/min with and without cutting fluid. A design of experiments (DOE) and an analysis of variance (ANOVA) have been made to determine the effects of each parameter on the tool wear and the surface roughness. It is being inferred that cutting speed has the main influence on the flank wear and as it increases to 175 m/min, the flank wear decreases. The feed rate has the most important influence on the surface roughness and as it decreases, the surface roughness also decreases. Also, the application of cutting fluid results in longer tool life and better surface finish.

Keywords. Machining; stainless steel 304; turning parameters; ANOVA.

1. Introduction

Austenitic stainless steels are widely used in cutlery, sinks, tubing, dairy, food and pharmaceutical equipments as well as in springs, nuts, bolts and screws due to their high strength and high corrosion and oxidation resistance. AISI 304 stainless steel finds its application in air craft fittings, aerospace components such as bushings, shafts, valves, special screws, cryogenic vessels and components for severe chemical environments. It is also being used for welded constructions in aerospace structural components (Anthony Xavior & Adithan 2009). Austenitic stainless steels are considered difficult to make a machine. Machining is the widespread metal shaping process in the manufacturing industry in which a sharp tool is used to mechanically cut the material to achieve the desired geometry. The cutting edge of the tool serves to separate chip

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from the work-piece. As the tool damage increases by wear or fracture, the surface roughness and accuracy of the machined surface deteriorates. The most suitable way to judge tool life is by measuring the roughness of machined parts but this is not always easy or cost-effective. An alternative is to monitor the amount of flank wear because it is the flank wear that influences work-piece surface roughness and accuracy (Childs *et al* 2000). Machining of AISI 304 is more complex compared to the machining of other low-alloy steels due to some characteristics such as having low heat conductivity, high deformation hardening and mechanical and microstructural sensitivity to strain and stress rates (Akasawa *et al* 2003; Kopak & Sali 2001). As a matter of fact, one characteristic feature of machining stainless steels is built-up-edge (BUE) formation, so that the chip being formed has a strong tendency to weld to the rake face of the tool and when it is broken away, it may bring with it a fragment of the tool, particularly when cutting with cemented carbide tools. Furthermore, the work hardening of the machined surface of austenitic steels makes the depth-of-cut region of the tool particularly sensitive to chipping, so problems such as poor surface finish and high tool wear are common. Machine vibrations and chatter phenomenon are other problems while machining these alloys (O'Sullivan & Cotterell 2002; Selinder *et al* 1998). During cutting, the cutting edge of tool is positioned at a certain distance below the original work surface. This corresponds to the thickness of the chip prior to chip formation, t_0. As the chip is formed along the shear plane its thickness increases to t_C. The chip thickness after cutting is always greater than the corresponding thickness before cutting (Groover 2007). Naturally a chip will curl after it flows out; chip curl radius and chip thickness influence tool life. Therefore, the study of chip-breaking is very important for optimizing the machining process especially in ductile materials such as AISI 304. Nakayama presented a chip-breaking criterion using material stress analysis for chip curl study (Avanessian 2005). Several attempts have been made to improve the machinability of stainless steels. Free cutting austenitic stainless steels with high sulfur content have been developed in order to facilitate cutting operations (M'Saoubi *et al* 1999). Tekiner & Yesilyurt (2004) investigated the cutting parameters for turning of AISI 304 stainless steel by considering the process sound and observed that cutting sound pressure levels decreased parallel to positive results occurred in chip removal. Korkut *et al* (2004) tried to determine the effects of cutting speed on flank wear and surface roughness in the machining of austenitic stainless steels. Abou-El-Hossein & Yahya (2005) presented the results of a study on tool wear of new developed multilayered carbide inserts while end milling of this alloy. Chow *et al* (2008) studied the friction drilling of AISI 304 alloy to show the important effects of process parameters on machining characteristics and to find the optimal geometric shape of the friction drills.

In this experimental study an attempt has been made to find out the effects of cutting speed, feed rate and cutting fluid on the turning efficiency of AISI 304 stainless steel. The experiments were performed with a tungsten carbide tool at five different cutting speeds and three various feed rates under dry and wet conditions. Consequently, the effects of the tow process parameters on the flank wear, surface roughness, built up edge size, chip curl radius and chip thickness are presented and the vital role of process parameters in heat generation and the effect of thermal concentration on the machining characteristics are analysed according to Nakayama's chip-breaking criterion.

2. Experimental procedure

Turning tests have been carried out on the samples with 250 mm length and 40 mm diameter. Chemical composition of the test samples is shown in table 1. A CNC lathe machine, model

Table 1. Chemical composition of AISI 304 stainless steel.

C	Cr	Ni	Mn	Si	Co	P	S	Ti	Nb	Fe
0.0466	18.07	8.11	1.37	0.46	0.40	0.028	0.0006	0.00	0.00	71.514

of CK7150A and TiC coated inserts form DMSC Tools Co. of China have been used in the experiments.

Samples have been machined at five various cutting speeds of 100, 125, 150, 175 and 200 m/min and three different feed rates of 0.2, 0.3 and 0.4 mm/rev with 2 mm constant depth of cut. All the experiments were performed under dry conditions and were repeated with a water-miscible cutting fluid.

In the design of experiments (DOE) the full factorial method was used in order to measure the effects of all levels of the process parameters (Roy 2001; Esme 2009). Critical machining parameters and their levels are shown in table 2. Flank wear, surface roughness, chip thickness, chip curl radius and built up edge size have been measured as output parameters to evaluate the machining efficiency.

3. Results and discussion

An ANOVA (analysis of variance) was made on the test results with Minitab software while each value was the average of three replications for each of the thirty different conditions. Tables 3 and 4 show the P-value and the contribution of each parameter for flank wear and surface roughness respectively. From the results it is inferred that cutting speed has more influence on flank wear and feed rate has more effect on surface roughness.

The P-value is a statistical index used in the analysis of variance. In the sense of statistical significance, the lower the P-value, the more significant is the tested parameter. Often the analysed parameter is considered as significant when the P-value is less than 0.05. In this study, the significance of all three parameters was proved since the P-values of all parameters were less than 0.05. Thus, it seems to be important to study the effects of each of the three process parameters on the machining characteristics.

From the ANOVA table for flank wear (table 3) it is found that the cutting speed with 62.28% contribution is the most significant parameter that affects the tool wear of AISI 304 material while turning. Figure 1 shows the effect of cutting speed on the flank wear under dry and wet conditions.

According to figure 1 with increasing the cutting speed from 100 m/min to 175 m/min, the flank wear decreases considerably. But it begins to increase by increasing the cutting speed more than 175 m/min. Also an increase in the feed rate from 0.2 mm/rev to 0.4 mm/rev increases the

Table 2. Critical parameters and their levels.

NO.	Machining parameters	unit	Level 1	Level 2	Level 3	Level 4	Level 5
1	Cutting speed	m/min	100	125	150	175	200
2	Feed rate	mm/rev	0.2	0.3	0.4		
3	Cutting fluid		dry	wet			

Table 3. ANOVA for flank wear.

Predictor	Sum of squares	Contribution (%)	P-value
Cutting speed	0.141135	62.28	0.000
Feed rate	0.014580	6.43	0.017
Cutting fluid	0.012813	5.65	0.024
Residual Error	0.058058	25.62	
Total	0.226587		

flank wear. The same trend is observed under both dry and wet conditions; also it is observed that the use of cutting fluid has increased tool life.

From the ANOVA table for surface roughness (table 4) it is found that the feed rate with 54.18% contribution is the most significant parameter that affects the surface roughness of AISI 304 alloy while machining. Figure 2 presents the effects of cutting speed and feed rate on the surface roughness without and with cutting fluid. It is observed that increasing the feed rate from 0.2 mm/rev to 0.4 mm/rev causes the surface roughness to increase. But an increase in the cutting speed leads to a decrease in the surface roughness. Also, it is found that the cutting fluid had a positive effect on the surface finish.

Figure 3 presents the chip curl radius while figure 4 indicates the chip thickness at different cutting speeds under dry and wet conditions. It is inferred from figure 3 that the chip curl radius and cutting speed are directly proportional, as increasing the cutting speed from 100 m/min to 200 m/min increases the chip curl radius. It is observed in figure 4 that the chip thickness is inversely proportional to the cutting speed, since increasing the cutting speed results in decreasing the chip thickness. Also it is inferred that the use of cutting fluid improves machining characteristics by increasing the chip curl radius and decreasing the chip thickness through promotion of plastic flow (De Chiffre 1977).

Heat generation and thermal concentration phenomenon can be analysed with the following Equation (Groover 2007).

$$r = \frac{t_0}{t_C} = \frac{\sin\phi}{\cos(\phi - \alpha)}, \tag{1}$$

where r is the chip ratio, t_0 is the depth of cut, t_C is the chip thickness, α is the rake angle and ϕ is the shear plane angle.

According to Equation 1, the high thickness leads to the high shear plane angle and as a result more energy is consumed to deform the material. It means that more heat will be generated and concentrated at the cutting edge since the thermal conductivity of AISI 304 alloy is low.

Table 4. ANOVA for surface roughness.

Predictor	Sum of squares	Contribution (%)	P-value
Cutting speed	2.1850	27.79	0.000
Feed rate	4.2596	54.18	0.000
Cutting fluid	1.0305	5.65	0.000
Residual Error	0.3860	13.10	
Total	7.8611		

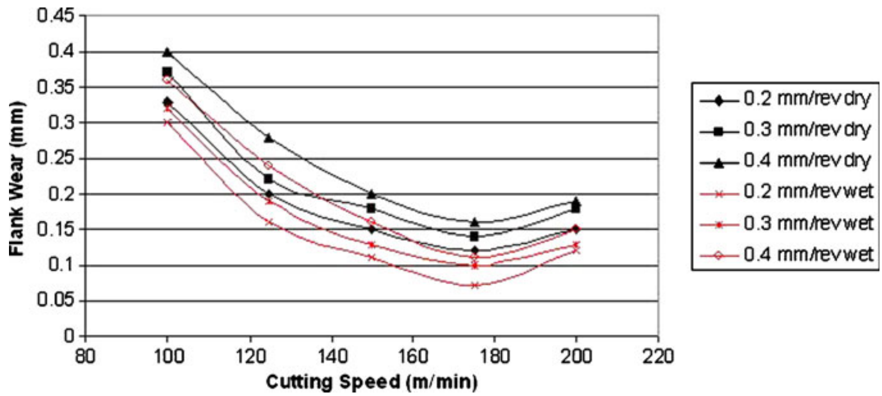

Figure 1. The effect of cutting speed on the flank wear.

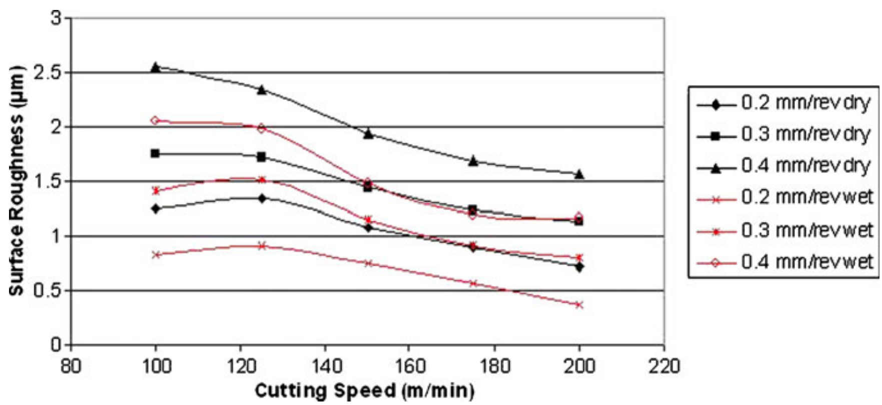

Figure 2. The effect of cutting speed on the surface roughness.

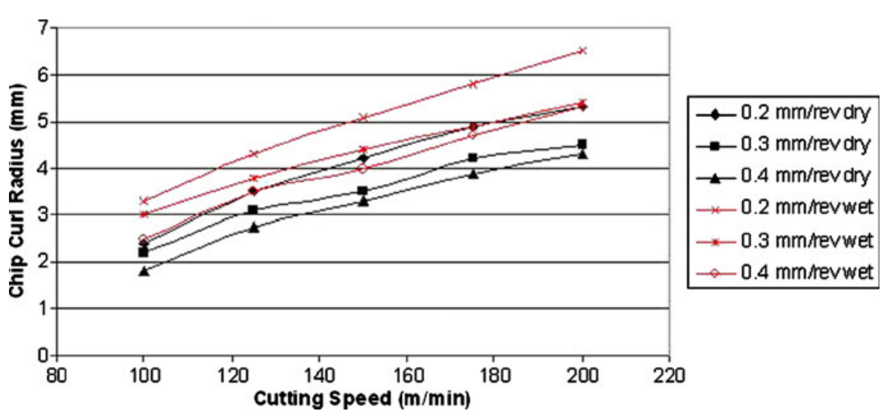

Figure 3. Chip curl radius at different cutting speeds.

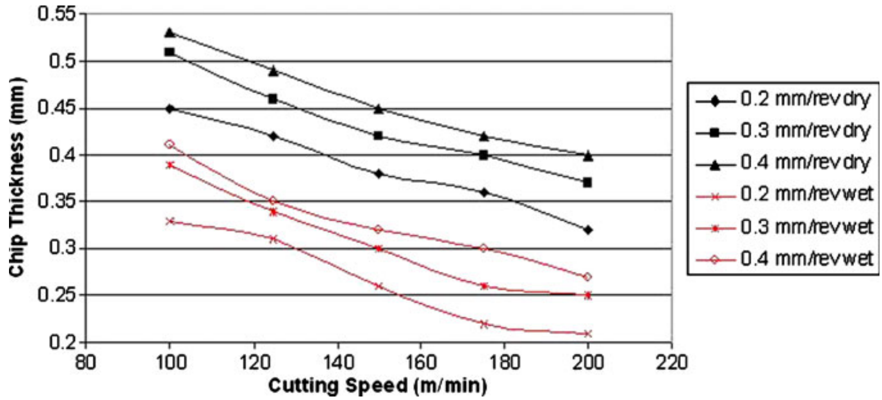

Figure 4. Chip thickness at different cutting speeds.

On the other hand, at low speeds, the high thickness results in the high chip ratio (r) that causes the chip to have a small area that cannot remove the heat efficiently.

The role of cutting fluid is so important in removing the generated heat from the cutting edge since the cutting fluid provides lubrication between the work piece and tool and also removes the generated heat during machining (Anthony Xavior & Adithan 2009). For this reason a water-miscible fluid was used due to its better cooling properties.

At higher speeds, as shown in figures 3 and 4 the chip thickness decreases and the chip curl radius increases. According to Nakayama's chip-breaking criterion, it is considered that when the actual chip fracture strain (ε) is smaller than the tensile strain of the chip (ε_B), the chip will break. It is noted that the ε is proportional to the ratio of chip thickness and chip curl radius (Li, 1990):

$$\varepsilon_B \propto \frac{t_C}{R_0}, \tag{2}$$

where, t_C is the chip thickness and R_0 is the chip up-curl radius.

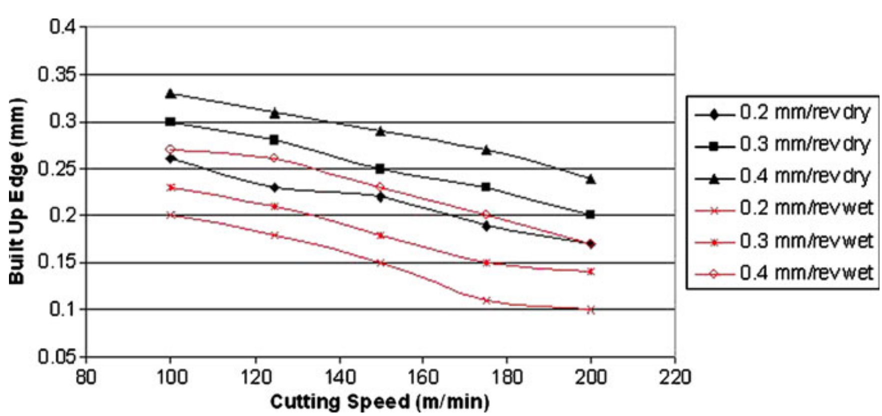

Figure 5. The effect of cutting speed on the built up edge.

Breaking chips with low thicknesses and high curl radii means, breaking with small strains. The smaller strain results in less energy consumption and less heat generation at the cutting edge.

As mentioned above, at low cutting speeds the tool wear is very high. Because of the large amount of heat and the lack of efficient heat removal, due to the low thermal conductivity of the material and the small area of the thick chips. But it decreases significantly by increasing the cutting speed.

Since AISI 304 is a ductile alloy, the built up edge phenomenon can affect the surface roughness seriously. The formation of built up edge leads to fluctuation of cutting force, deterioration in the surface finish, drastic reduction in tool life and so on (Chattopadhyay *et al* 2009). As indicated in figure 5, built-up-edge formation is in relation with cutting speeds and feed rates. So that, at lower speeds and higher feed rates, built-up-edge phenomenon results in poor surface finish. According the above figures, by increasing the cutting speed, decreasing the feed rate and using the cutting fluid, the built-up-edge size decreases and the surface state improves considerably. These observations agree with the research by Sun *et al* (1998).

On the other hand, increasing the cutting speed and decreasing the feed rate lead to smaller chip thicknesses and higher curl radii so that the machining forces and the machine vibrations decrease, and afterwards the surface finish improves significantly. Also the cutting fluid increases the efficiency of turning due to increasing tool life, improving surface finish, reducing cutting forces and vibrations.

4. Conclusions

The effect of influential turning parameters of cutting speed and feed rate on turning of AISI 304 stainless steel was studied under two conditions of dry and wet machining and the following conclusions are drawn:

(i) The results indicate that the process parameters of cutting speed and feed rate have significant effects on the quality of turning of AISI 304 stainless steel.
(ii) Tool flank wear is closely related to the cutting speed, so that it decreases significantly by increasing the cutting speed up to 175 m/min. The main reason for flank wear is the lack of efficient heat removal due to the low conductivity of AISI 304 alloy, the shape and size of the chips formed.
(iii) Surface roughness is mostly affected by the feed rate, so that the surface finish can be improved by decreasing the feed rate as well as increasing the cutting speed. Since, at higher speeds and lower feed rates built up edge decreases, so do the cutting forces and machine vibrations.
(iv) The application of cutting fluid results in longer tool life compared to dry cutting.
(v) The cutting fluid demonstrates to improve the tribological characteristics of the work piece.
(vi) It is observed that the optimum condition of cutting speed of 175 m/min and feed rate of 0.2 mm/rev exhibits superior turning properties provided the cutting fluid is used.

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