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Effect of cutting fluids and cutting conditions on surface integrity and tool wear in turning of Inconel 713C

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Abstract. The trend toward downsizing of engines helps to increase the number of turbochargers around Europe. As for the turbocharger, the temperature of the exhaust gas is so high that the parts made of nickel base super alloy Inconel 713C are used as high temperature strength metals. External turning of Inconel 713C which is used as the actual automotive parts was carried out. The effect of the cutting fluids and cutting conditions on the surface integrity and tool wear was investigated, considering global environment and cost performance. As a result, in the range of the cutting conditions used this time, when the depth of cut was small, the good surface integrity and tool life were obtained. However, in the case of the large corner radius, it was found that the more the cutting length increased, the more the tool wear increased. When the cutting length is so large, the surface integrity and tool life got worse. As for the cutting fluids, it was found that the synthetic type showed better performance in the surface integrity and tool life than the conventional emulsion. However, it was clear that the large corner radius made the surface roughness and tool life good, but it affected the size error etc. in machining the workpiece held in a cantilever style.

1. Introduction

The automobile industry has been making better use of the engines equipped with turbochargers which control the amount of the air and make the exhaust gas clean in order to cope with the present environmental restrictions. The trend toward downsizing of engines helps to increase the number of turbochargers around Europe [1]. As for the turbocharger, it is necessary for measures of the lower pollution gas of the automotive engines. And the demand for the lower pollution gas may be increasing in the future [2], [3]. The temperature of the exhaust gas is so high that the parts made of nickel base super alloy are used as high temperature strength metals [4]. The alloy is one of difficult–to-cut materials and many studies on it have been carried out so far [5]–[12]. However, there are very few practical techniques for using the actual automotive parts. This study dealt with Inconel 713C as the nickel base super alloy. The workpiece was machined in the same size as the actual automotive parts. The effect of the cutting fluids and cutting conditions on the surface integrity and tool wear was investigated, considering global environment and cost performance.

2. Experimental

2.1. Workpiece Material

The valve stem bars of Inconel 713C were used as the workpiece material. They are part of the westgate type turbocharger. Inconel 713C which is the cast type nickel base super alloy is used so that it can endure the high exhaust gas temperature which amounts to 900 ℃ [4]. The suitable condition of the precise machining for Inconel 713C is required so that the valve stem bars may acquire high quality of the surface integrity. Grinding has been carried out as finishing process. However, external turning was used in this experiment, given the running cost and machining time. Since the shape of workpiece disturbs its correct chucking, the cantilever holding has to be used. As a result, the dimension error may give a little damage to surface integrity. Tables 1, 2 and 3 show the nominal compositions, the physical properties and the mechanical properties of Inconel 713C, respectively [13].

Table 1. Nominal chemical composition of Inconel 713C.

C	Cr	Mo	Nb	Al	Ti	Zr	B	Ni
0.12	12.5	4.2	2.0	6.1	0.8	0.1	0.012	bal

2.2. Experimental Conditions

In the experiment, CNC lathe was used as shown in Fig. 1. Under the cutting conditions shown in Table 4, the PVD coating positive throwaway inserts were applied to the Inconel 713C test bar, 8.1 mm in the external diameter and 68 mm in length. This coating layer is super-multi layered coating with ultra-thin (nanometer) layers of TiAlN and AlCrN, alternately stacked up to 1,000 layers, and superior in heat and wear resistance [14]. The projected part in the cantilever state from lathe chuck was 35 mm. Generally, in the case of machining for the heat-resisting alloy, the positive rake angle throwaway insert with a sharp cutting edge equivalent to the smallest possible honing is used for machining so that the cutting edge may not be filled with cutting heat. Thus, the rake angle was held constant at 8 degrees. Table 4 shows the cutting conditions. In this experiment, three types of cutting fluids were used: synthetic soluble as the sample A, an emulsion including a sulfur type extreme pressure additive as the sample B, a synthetic emulsion including a sulfur type extreme pressure additive as the sample C. Each feature is shown in Table 5. As a cutting fluid, each of the types was diluted 10 times. The cutting fluid was added to the cutting point at the rate of 10 L/min with the external nozzle. After machining, arithmetic average roughness Ra in the direction of the tool feed motion were measured with the surface measuring instrument by stylus method, at the position at which the circumference was divided equally into three. Furthermore, size error and roundness were measured with the coordinate measuring machine. Tool wear was measured with the toolmakers microscope. The number of cutting times was one in the previous study [15], but by varying it in this study, surface integrity and tool wear were investigate.

Table 2. Physical properties of Inconel 713C.

Density	Melting range	Specific heat			Thermal conductivity		
		At 21 ℃	At 538 ℃	At 1093 ℃	At 93 ℃	At 538 ℃	At 1093 ℃
(g/cm^3)	(℃)	(J/kgK)	(J/kgK)	(J/kgK)	(W/mK)	(W/mK)	(W/mK)
7.91	1260-1290	420	565	710	10.9	17.0	26.4

Mean coefficient of thermal expansion		
At 93 ℃	At 538 ℃	At 1093 ℃
(×10-6/K)	(×10-6/K)	(×10-6/K)
10.6	13.5	17.1

Table 3. Mechanical properties of Inconel 713C.

Tensile strength		0.2 yield strength		Tensile elongation	
At 21 ℃	At 538 ℃	At 21 ℃	At 538 ℃	At 21 ℃	At 538 ℃
(MPa)	(MPa)	(MPa)	(MPa)	(%)	(%)
850	860	740	705	8	10

Dynamic modulus of elasticity	
At 21 ℃	At 538 ℃
(GPa)	(GPa)
206	179

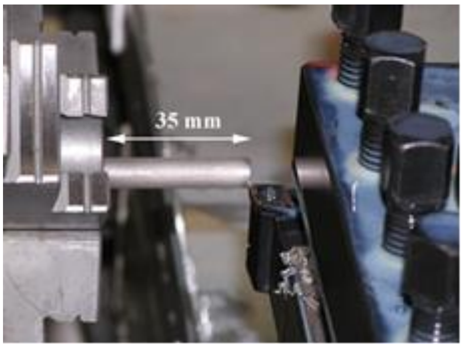


Figure 1. Cutting method.

Table 4. Cutting conditions

Diameter *D* (mm)	φ8.1
Rake angle γ (deg.)	8
Corner radius *rε* (mm)	0.2, 0.4
Depth of cut *a* (mm)	0.1, 0.5
Cutting speed *V* (m/min)	30
Feed rate *f* (mm/rev)	0.01
Cutting length *L* (m)	50, 100, 150, 200, 300

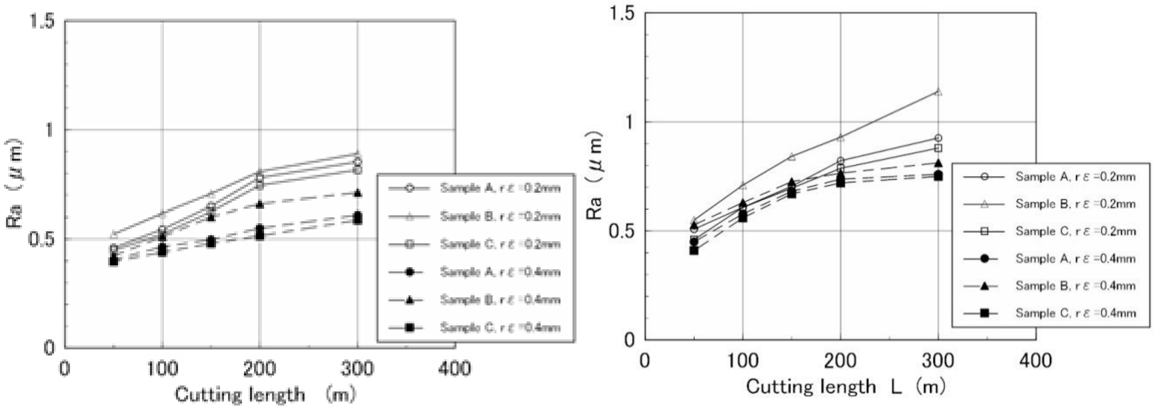
Table 5. Cutting fluids

Cutting fluids	Sample A	Sample B	Sample C
Type	Synthetic soluble	Emulsion	Synthetic emulsion
Density (g/cm^3(15 ℃))	0.98	0.938	1.012
Surface tension (mN/m(25 ℃))	32.9	34	25.2
S (Sulfur)	-	○	○
P (Phosphorus)	-	-	-
B (Boron)	-	-	-
pH	9.3	9.7	9.87

3. Results and Discussions

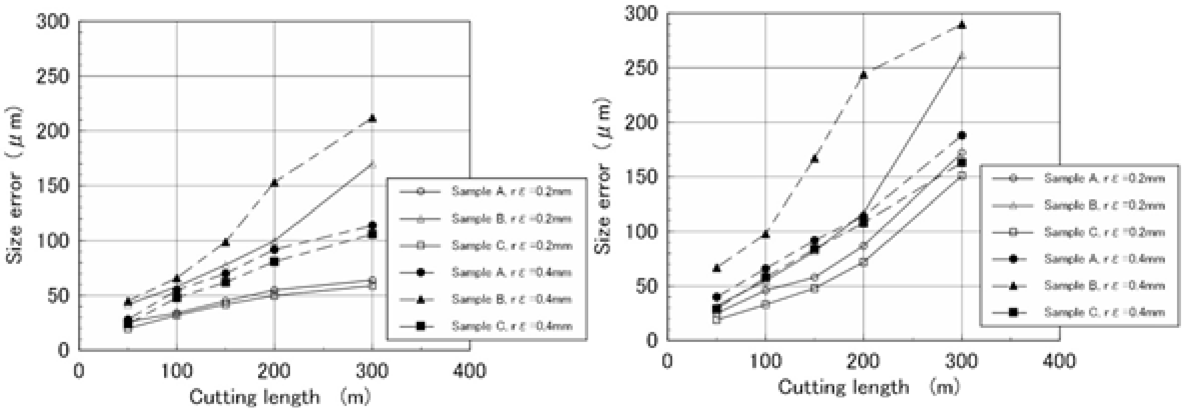
Figure 2 shows the relation between the cutting length and the arithmetic average roughness Ra. The figure (a) and the figure (b) show the depth of cut *a* is 0.1 mm and 0.5 mm, respectively. In this figure, the white mark and the black one show the corner radius *rε* is 0.2 mm and 0.4 mm, respectively. These display methods are the same in Figs. 2 to 6. In the cases of depth of cut *a* = 0.1 mm and 0.5 mm, it is found from this figure that the larger the cutting length *L* is, the worse Ra becomes. And the larger the corner radius *rε* is, the better Ra becomes. Under the same condition under which the feed rate *f* and depth of cut *a* are the same, it is found that the more the corner radius *rε* increases, the better the theoretical roughness becomes. As for the effect of the cutting fluids, the synthetic emulsion of the sample C was somewhat excellent. In addition, in the case of the sample C, the adhesion area cannot be confirmed in the cutting edge after machining, it seems to be superior in lubricity. It is considered that the wetting on the tip near the cutting edge and the surface of the work material performed efficiently, because of the smallest surface tension of the sample C in all the cutting fluids used this time. In the case of the large depth of cut, such as *a* = 0.5 mm, Ra became worse on the whole. However, the synthetic soluble showed as good results in the sample A as in the sample C. Therefore, in the case of these cutting fluids, it was found that Ra of *rε* = 0.4 mm settled within 1 μm even if the cutting length *L* was 300 m.

Figure 3 shows the effects of the cutting conditions on the size error. It means the difference in diameter between the workpiece measured by the end retainer setting with CNC lathe before and after machining. As for the effect of the cutting length, the more the cutting length *L* increases, the greater the size error becomes, like the previous result of the surface roughness, as seen from this figure. However, as for the effect of the corner radius *rε*, the more the corner radius *rε* decreases, e.g. at 0.2



(a) *a*=0.1mm (b) *a*=0.5mm

Figure 2. Effects of cutting conditions on Ra.



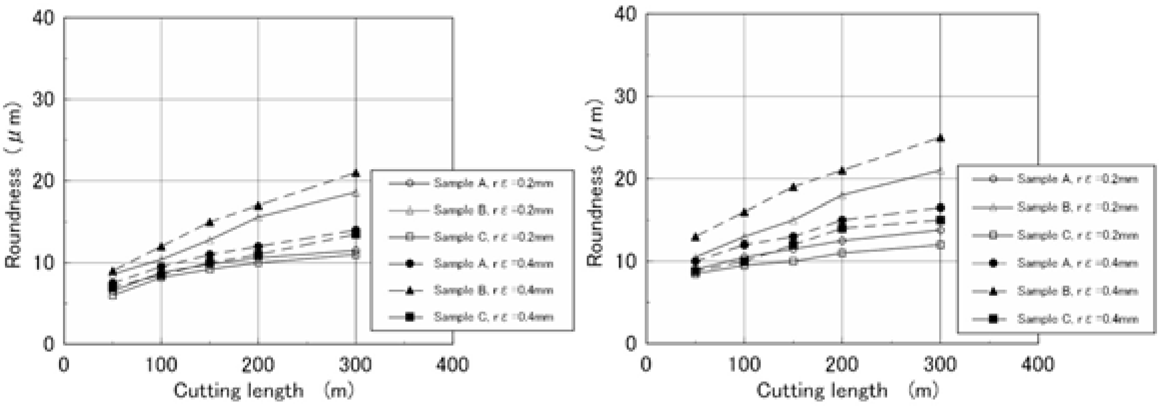
(a) *a*=0.1mm (b) *a*=0.5mm

Figure 3. Effects of cutting conditions on size error.

mm, the less the size error becomes, unlike the effect on the surface roughness. Furthermore, in the case of large depth of cut, a = 0.5 mm, it is found that the size error gets extremely worse. Since the workpiece was held and machined in the cantilever style, the deflection of the workpiece changed greatly. Thus, the more the corner radius increases, the more gradually the cutting force also increases. When the depth of cut a = 0.1 mm, the size error of $r\varepsilon$ = 0.4 mm by using emulsion is over 100 μm at the cutting length L = 150 m. However, the synthetic emulsion and the synthetic soluble enable the size error to keep below 100 μm up to the cutting length L = 200 m.

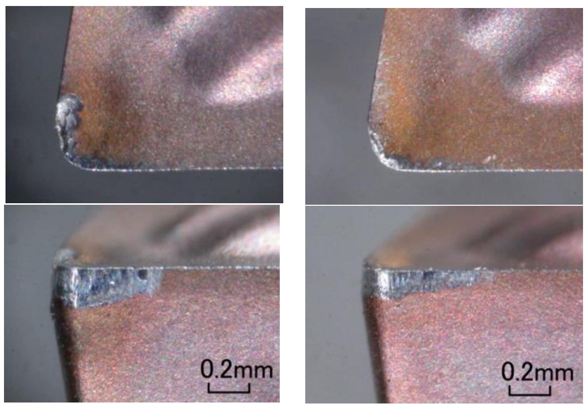
Figure 4 shows the effects of the cutting conditions on the roundness. It is found that the more the cutting length L increases, the more the roundness increases. In the case of the roundness, the more the corner radius $r\varepsilon$ decreases, the better roundness becomes, like the previously mentioned case of the size error. Furthermore, when the depth of cut a becomes larger, 0.5 mm, it is found that the roundness gets somewhat worse. As for the cutting fluids, the synthetic emulsion and the synthetic soluble are more effective to the roundness than the conventional emulsion. The synthetic emulsion and the synthetic soluble enable the roundness to keep below 20 μm up to the cutting length L = 300 m.

In this way, the effects of the cutting condition on the surface integrity after machining were showed. Figure 5 shows the photo of the tool wear in the case of the cutting length L = 200 m. From these figures, it is found that the tool wear by using the synthetic emulsion becomes smaller than by using the emulsion. Figure 6 shows the effects of the cutting condition on the tool wear. As for one of the causes that the large cutting length made the surface integrity get worse as shown in Figs.2 to 4, it is consider that the more cutting length increase, the more tool wear increases. At the cutting length L = 50 m, the tool wear of the depth of cut a = 0.5 mm tends to be somewhat larger than of a = 0.1 mm. In



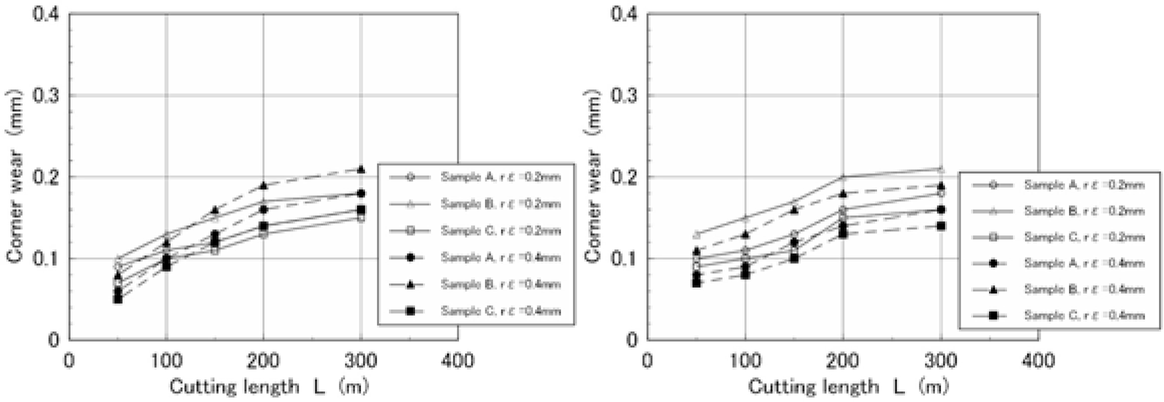
(a) *a*=0.1mm (b) *a*=0.5mm

Figure 4. Effects of cutting conditions on roundness.



(a) Emulsion (b) Synthetic emulsion

Figure 5. Photo of tool wear (a = 0.5 mm, $r\varepsilon$ = 0.2 mm).



(a) *a*=0.1mm (b) *a*=0.5mm

Figure 6. Effects of cutting conditions on tool wear.

the case of the depth of cut a = 0.5 mm, on the whole, the more the corner radius increases, the more the tool wear decreases. In the case of a = 0.1 mm, when the cutting length increases, the tool wear of the large corner radius gets worse than of the small one. It is considered that when the cutting length increases, the cutting edge becomes dull, so the tool of the large corner radius tends to slip easily due to the small depth of cut. For all this, the synthetic emulsion and the synthetic soluble enable the tool wear to keep bellow 0.2 mm up to the cutting length L = 300 m.

4. Conclurion

External turning of Inconel 713C which is the cast type nickel base super alloy and used as the valve stem of the turbocharger parts was carried out. And the influence of the cutting condition on surface integrity was investigated. Furthermore, the surface integrity and tool wear were investigated experimentally by comparing the performance of the cutting fluids between the synthetic type and the conventional emulsion. As a result, in the range of the cutting conditions used this time, when the depth of cut was small, the good surface integrity and tool life were obtained. However, in the case of the large corner radius, it was found that the more the cutting length increased, the more the tool wear increased. When the cutting length is so large, the surface integrity and tool life got worse. As for the cutting fluids, it was found that the synthetic type showed better performance in the surface integrity and tool life than the conventional emulsion. However, it was clear that the large corner radius made the surface roughness good, but it affected the size error etc. in machining the workpiece held in a cantilever style.

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