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Dry and cryogenic milling of AISI 4340 alloy steel

Shalina Sheik Muhamad *, Jaharah A. Ghani, Afifah Juri, Che Hassan Che Haron

Faculty of Engineering and Build Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, MALAYSIA.
*Corresponding author: P91996@siswa.ukm.edu.my

KEYWORDS

Surface roughness
Alloy steel AISI 4340
Dry and cryogenic
Effect machining parameter

ABSTRACT

Nowadays the quality of machined surface has become the main problem due to the demand rate of life span, performance, and reliability of a machined product. The study of the component's surface integrity is an important aspect of avoiding failure. The purpose of this research is to investigate the effect of milling parameters on cutting temperature and surface roughness of AISI 4340 with cutting speeds of 180- 220 m/min, feed rate of 0.1- 0.2 mm/tooth and depth of cuts of 0.3- 0.7 mm. The cutting temperature was simulated using Third Wave AdvantEdge v6. 4 software under dry conditions using uncoated carbide cutting tool. The average surface roughness was measured experimentally during the milling under the dry and cryogenic conditions using a portable surface-roughness measurement device. The analysis of variance was applied in order to determine the effects of the control factors for temperature. The results revealed that cutting speed is the most influential machining process parameter on cutting temperature in the end milling process. A significant 14-24 % average surface roughness decrement was observed in cryogenic machining compared to dry machining.

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1.0 INTRODUCTION

Nowadays manufacturing industries are increasingly growing and developing toward producing products which possess high quality performance. This quality is connected to the aspects of surface integrity, dimensional accuracy, burrs and other types of defects which occur in the machining industry. Finite element method (FEM) is a very useful tool for machining simulation purposes (Kilicaslan, 2009). Several studies have been conducted for machining simulation globally. With the aid of finite element analysis, users can generate analysis results much faster and can also present results which are reliable without conducting physical tests (Lauro et al., 2015).

The AISI 4340 steel is mainly used for aircraft components, aerospace components such as bushes, shafts, valves, unique screws, carnage vessels and components due to its resistance to chemical action. In addition, it is also widely used in the automotive industry and in mechanical engineering technology. Most of these products require a machine which is specific to the manufacturing process (Sohrabpoor et al., 2015).

Cryogenic machining is the cooling method of cutting tool points and /or workpieces during the material removal process. Coolant material used is normally nitrogen liquid (LN) with cooling of up to -196°C (Umbrello et al., 2012). Pu et al., (2012) have been researching crystalline magnesium alloys to improve their integrity. Researchers found that when performing cryogenic machining, using a large radius edge tool leads to increased surface integrity in terms of better surface finish (Pu et al., 2012). There was a study produced by Kumar (2013) where he found that the application of specific cryogenic cutting conditions can produce better fractional fractures during machining, with acceptable debris and with reduced debris. Consequently, when applying specific cryogenic cutting conditions, more uniform and smaller fragments can be observed in the formation of iron fragments produced after machining (Kumar, 2013).

There have been many types of problems in surface integrity which have been reported in previous studies. Among the problems which have been reported are residual stress, white layer and hardening layer work, and changes in microstructure. The surface integrity study covers mechanical properties (residual stress, hardness), metallurgical effect (phase transformation, microstructure and related properties disparities) and topological parameters (surface finish and other topographic features of the surface) on the workpiece during processing (M'Saoubi et al., 2008).

Typical ranges of the average surface roughness (Ra) values attainable in many traditional machining operations under normal conditions and non-traditional processes are illustrated in Figure 1. Higher or lower values of Ra may be obtained under various machining conditions, such as rough, medium or finishing operations. From Figure 1, Ra parameter of 1.6-6.3 µm can be produced in the milling process (Grzesik et al., 2010).

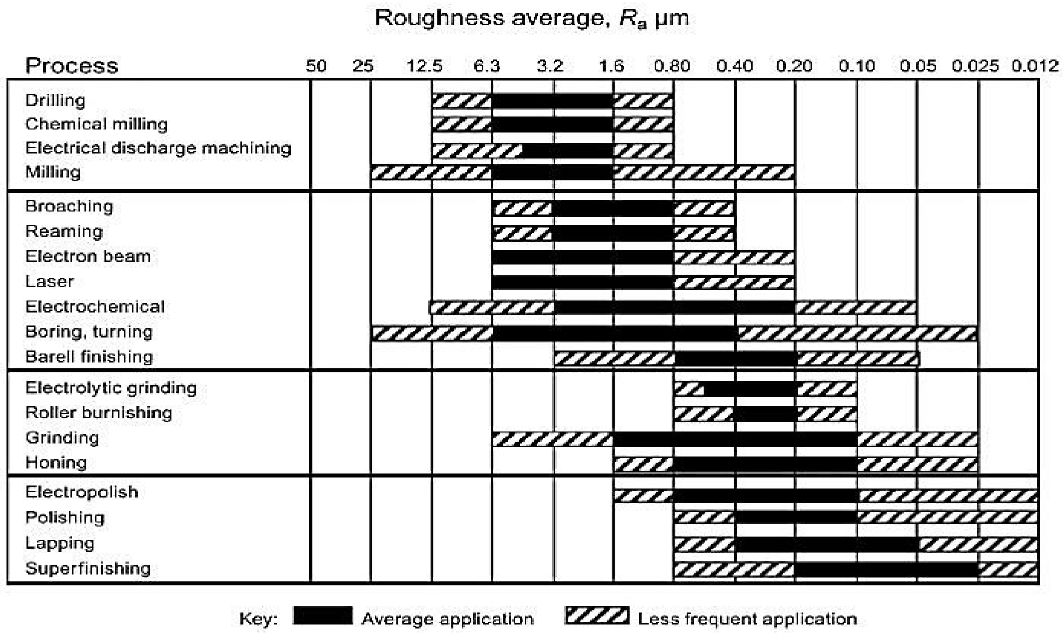


Figure 1: Typical ranges of surface finish from common machining processes (Grzesik et al., 2010).

The results of research conducted by Das et al., (2015), has shown that feed rates had significance on surface roughness while machining power was influenced by feed rate and cutting depth. It is proven that when feed rate increases, the surface roughness (Ra) of the work will also increase. In addition, it is also found that surface finishing improves with increase in cutting speed, which can control build up edge (BUE) formation. Increase in cutting speed will increase the surface roughness, which can be explained by the possibility of chatters formation due to vibrations (Das et al., 2015).

Similar findings were reported by Stipkovic et al., (2016) during machining of hardened AISI 4140 alloy steel which focused on surface finishing of a machined surface. Also, it was found that higher feed per tooth combined with higher cutting depth generated a worse surface finishing. Based on these results, it can be stated that the finishing milling of hardened steel with CBN tool without the presence of cutting fluid produced a surface finishing as good as by the grinding process, with the advantage of being faster and being environmentally friendly by eliminating the cutting fluid (Stipkovic et al., 2016).

Garcia et al., (2014) proved that cryogenic machining using LN is the best solution to machinability problems of components manufactured using AISI 4150 steel since it reduces machining problems of heating, leading to tool life improvement and better surface integrity of turned components. The surface integrity includes higher surface hardness, lower residual stresses and no white layers (Garcia et al., 2014).

Research has been conducted to investigate the influence of cutting parameters on cutting temperatures and cutting forces. Motorcu et al., (2016), investigated the effects of the control factors in the turning of AISI 4140 steel workpieces. It was found that cutting temperature increases depending on the increase of the cutting speed and the decrease of the depth of cut and the feed rate. The cutting speed is the most effective factor for the tool-chip interface temperature, with a contribution of 86.57 % (Motorcu et al., 2016).

A study was reported by Hamidon et al., (2016), during their machining operation of AISI H13 for different shapes of pockets. It was shown that for cutting temperature, cutting speed has the highest percentage of contribution, compared to feed rate and depth of cut. This is due to the adiabatic effect at high cutting speed caused by the trapped heat in the shear deformation zone. The heat cannot escape in the very short time during the process, causing highly localized temperatures in the chip (Hamidon et al., 2016).

In this paper, the simulation of cutting temperatures during the milling of AISI 4340 alloy steel was performed using various cutting parameters with Third Wave AdvantEdge v6. 4 software. The average surface roughness Ra was measured experimentally using a portable surface-roughness measurement device under dry and cryogenic conditions. The Taguchi design of the experiment was selected to find the relationships between the control parameters. The cutting speed (*Vc*), the feed rate (*fz*:) and the depth of cut (*ap*) were taken as control factors. This study intends to compare the surface roughness of a cryogenic application to a dry environment in the end milling of AISI 4340 alloy steel.

2.0 EXPERIMENTAL PROCEDURE

The first phase of the experimental procedure was the finite element method (FEM) which was conducted to determine whether the temperature generated was high enough for the grain refinement and phase transformation at the machined surface of AISI 4340 steel. The austenitising temperature for AISI 4340 is in between 774 °C – 810 °C. The analysis of variance (ANOVA) was used to determine the percentage of contribution of individual cutting parameters on temperature and force. After the screening of the FEM results, the significant factors were then tested in experimental runs under two cutting conditions: dry and cryogenic in terms of surface roughness.

2.1 Finite Element Simulation Setup

The commercial FEM software of Third Wave AdvantEdge (v6.4) was used to simulate the milling process in two dimensions (2D). Third Wave AdvantEdge is based on an updated Lagrangian formulation and employs an implicit integration scheme. The main machining response which was examined in this paper was the cutting temperature. Figure 2 shows the schematic model of orthogonal cutting condition. The cutting parameter for this study is shown in Table 1. Nine sets of simulation combinations were generated using Taguchi design of experiments, as shown in table 2.

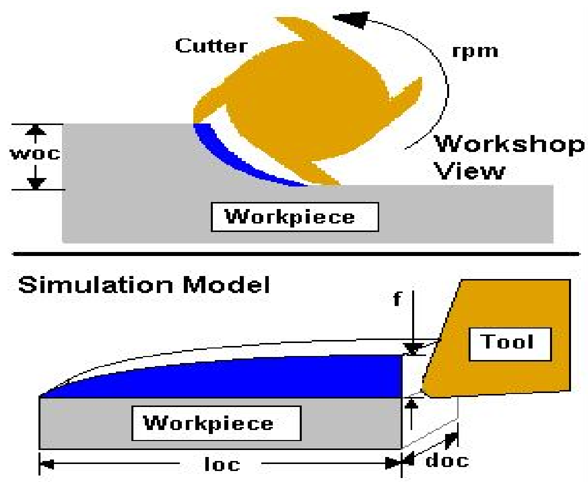


Figure 2: Simulation model (ThirdWaveSystems, 2015).

Table 1: Cutting parameters and their levels.

Cutting parameters	Level 1	Level 2	Level 3
Vc: Cutting speed (m/min)	180	200	220
fz: Feed (mm/tooth)	0.10	0.15	0.20
ap: Depth of cut (mm)	0.3	0.5	0.7

Table 2: Design of experiment.

Experiment	Cutting speed, *Vc* m/min	Feed , *fz* mm/tooth	Depth of cut, *ap* mm
1	180	0.10	0.3
2	180	0.15	0.5
3	180	0.20	0.7
4	200	0.10	0.5
5	200	0.15	0.7
6	200	0.20	0.3
7	220	0.10	0.7
8	220	0.15	0.3
9	220	0.20	0.5

The AISI 4340 used in the research was a high strength low alloy steel widely used in the automotive and aerospace industries, mainly manufactured as heavy duty shafts, gears, axles, spindles, couplings and pins, as well as some other parts. The operation was simulated using a carbide insert of the DNMA432 type which had a nose angle of 55 deg, without the use of a coolant. The experimental tests were carried out equivalent to the machining conditions used in the simulation test and the details of the tests have been listed in Table 3. The chemical composition of the AISI 4340 alloy steel has been tabulated in Table 4.

Table 3: Details of simulation test of AISI 4340 alloy steel.

Item	Description
Tool parameter	
Cutter diameter (mm)	20
Cutting edge radius (mm)	0.8
Rake angle (degree)	10
Relief angle (degree)	11
Rake length (mm)	6.6
Relief length (mm)	10
Maximum tool element size (mm)	0.1
Minimum tool element size (mm)	0.02
Mesh grading	0.1
Tool material	
Material	Carbide
Grade	K
Boundary condition	
Initial temperature (deg. C)	20
Length of cut (mm)	20
Workpiece meshing	
Suggested maximum element size (mm)	0.1
Suggested minimum element size (mm)	0.02
Cutting edge radius to det. min. elem. Size	0.6
Feed fraction to det. min. elem. Size	0.1
Workpiece properties	
Ultimate tensile strength (MPa)	1300
Yield strength (MPa)	1200
Hardness (Bhn)	372

Table 4: Chemical compositions for AISI 4340 from AdvantEdge material library.

Element	C	Cr	Mn	Mo	Ni	P	S	Si
Weight (%)	0.405	0.8	0.7	0.25	1.875	0.035	0.040	0.275

2.2 Experimental Setup

An AISI 4340 rectangular 200 mm x 100 mm x 100 mm box was milled under two conditions on a SPINNER CNC milling machine with a 15000 RPM maximum spindle speed. The experimental tests were carried out using uncoated carbide inserts and the details of the tests have been listed in Table 5. The machining test was carried out at the cutting speeds of 180 and 220 m/min. The feed rate was varied at 0.10 and 0.15 mm/tooth and the depth of cut employed was 0.3 mm. The parameters were chosen based on simulation results with the highest cutting temperature generated and the lowest depth of cut.

Table 5: Details of the experimental test of AISI 4340 alloy steel.

Item	Description
Cutting speed (m/min)	180 and 220
Feed rate (mm/tooth)	0.10 and 0.15
Depth of cut (mm)	0.3
Cutting fluid	Dry and cryogenic (LN)

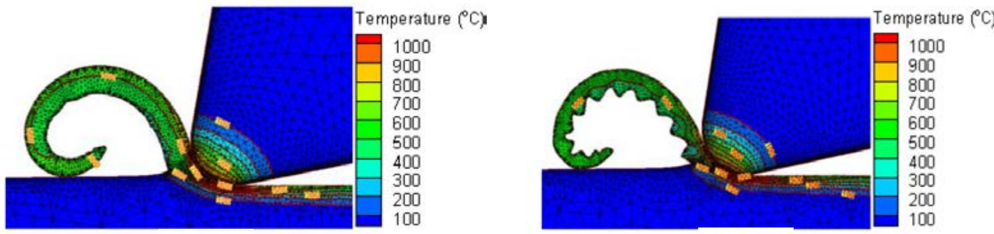
For the cryogenic machining, a cylindrical liquid nitrogen (LN) tank was connected to a flexible hose and a copper pipe was used as a nozzle pointing to the cutting zone. The distance between the tip of the nozzle to the cutting point was fixed at 2 cm. The surface roughness was measured using a Mitutotyo Surftest SJ-310 portable surface roughness tester. The arithmetic average roughness value (Ra) in micrometer (μm) was taken at the beginning of the run of each experimental test. The measurement was performed three times at three different locations and the average value was calculated to represent the average value of surface roughness. Figure 3 shows a Mitutotyo Surftest SJ-310 portable surface roughness tester which was used on the machined surfaces. Analysis of variance (ANOVA) was used for analyzing the data obtained both in the simulation and experimental work.

Figure 3: Placement of surface roughness tester on the workpiece's surface.

3.0 RESULTS AND DISCUSSION

3.1 Cutting Temperature

The isothermal contours of the temperature distributions for dry condition are shown in Figure 4 (a) at *Vc*: 180 m/min, *fz*: 0.1 mm/tooth, *ap*: 0.3 mm and (b) *Vc*: 220 m/min, *fz*: 0.1 mm/tooth, *a*p: 0.3 mm. Based on the simulation results, the highest temperature constantly occurs around the middle tool-chip contact area on the rake face, which can be associated with the secondary deformation zone which has been identified as the main source of the temperature rise on the cutting insert (Abukhshim et al., 2006). It is shown that for different machining parameters, different chip shapes were formed. Table 6 shows the temperature simulation results.



(a) (b)

Figure 4 : Temperature distribution in dry milling of AISI 4340 using AdvantEdge simulation at (a) *Vc*: 180 m/min, *fz*: 0.1 mm/tooth, *ap*: 0.3 mm (b) *Vc*: 220 m/min, *fz*: 0.1 mm/tooth, *ap*: 0.3 mm.

Table 6: Cutting temperature simulation results.

Experiment	**Cutting speed,*Vc* m/min**	**Feed ,*fz* mm/tooth**	**Depth of cut, *ap* mm**	**Cutting temperature (^{0}C)**
1	180	0.10	0.3	959.99
2	180	0.15	0.5	975.74
3	180	0.20	0.7	948.03
4	200	0.10	0.5	953.34
5	200	0.15	0.7	962.45
6	200	0.20	0.3	978.13
7	220	0.10	0.7	969.64
8	220	0.15	0.3	1010.93
9	220	0.20	0.5	982.21

Table 6 confirms that the highest temperature was generated at a cutting speed of 220 m/min, a feed rate of 0.15 mm/tooth, and a depth of cut of 0.3 mm at 1010.93°C, while the lowest temperature generated was at a cutting speed of 180 m/min, a feed rate of 0.2 mm/ tooth, and a depth of cut of 0.7 mm at 948.033°C. The analysis of variance (ANOVA) was performed to determine the contribution of individual cutting parameters on temperature. The percentage of the parameters were as shown in table 7.

The ANOVA analysis from Table 7 shows that the cutting speed contributes 43.55 %, followed by the depth of cut at 28.08%, and the feed rate 26.25% of the temperature generated. Therefore, the cutting speed has the most significant effect on the temperature generated, which agrees with Das & Nayak (2012).

Table 7: ANOVA-temperature.

Parameter	DF	Seq SS	Contribution	Adj MS	F-Value	P-Value
Vc: Cutting speed (m/min)	2	1231.71	43.55%	615.85	20.51	0.046
fz: Feed (mm/tooth)	2	794.14	28.08%	397.07	13.23	0.070
ap: Depth of cut (mm)	2	742.58	26.25%	371.29	12.37	0.075
Error	2	60.04	2.12%	30.02		
Total	8	2828.46	100.00%			

3.2 Surface Roughness

The experimental results have been presented in Table 8. The average surface roughness value obtained was within the range of semi finishing in milling as in Figure 1. The feed rate had the highest influence on surface roughness. When feed rate increased from 0.1 mm/tooth to 0.15 mm/tooth, surface roughness value increased. Therefore, the feed rate has the most significant effect on the surface roughness, which is supported by Othman et al., (2018) , where they claimed that the surface roughness value increases with increased feed rate.

Table 8: Experimental results.

Run	Process parameters			Experimental results	
	Cutting speed,*Vc* m/min	**Feed, *fz* mm/tooth**	**Depth of cut, *ap* mm**	**Dry µm**	**Cryogenic (LN) µm**
(a)	180	0.10	0.3	0.34	0.256
(b)	220	0.15	0.3	0.35	0.300

These results are in agreement with Equation 1 (Grzesik et al., 2010) where high feed rates will produce a rougher machined surface. On the other hand, low feed rate will improve the machined surface finish when cutting while using the same value of tool nose radius.

$$\mathrm{Ra}=\frac{\mathrm{r}-\sqrt{\mathrm{r}^2-\left(\frac{ft}{2}\right)^2}}{2} \tag{1}$$

Where r is nose radius and *ft* is a feed per tooth.

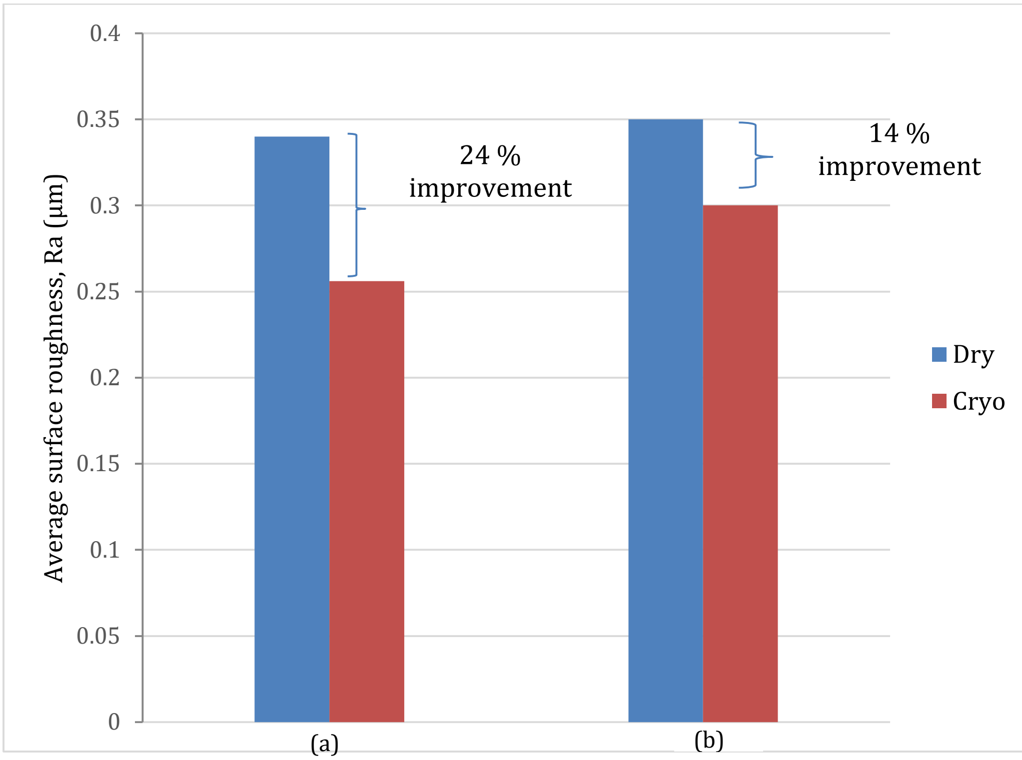


Figure 5: Average surface roughness in dry and cryogenic milling of AISI 4340 at (a) *Vc*: 180 m/min, *fz*: 0.1 mm/tooth, *ap*: 0.3 mm (b) *Vc*: 220 m/min, *fz*: 0.15 mm/tooth, *ap*: 0.3 mm.

From Figure 5 (a) and (b), the Ra measurements obtained in machining with cryogenic coolant were found to be largely and consistently superior to those obtained in dry machining. The average roughness of the cryogenic machined surface improved by about 14 % and 24 % compared to the dry milling. This might be due to the application of LN which reduces the coefficient of friction at the interfaces, which leads to better surface roughness (Natasha et al., 2014). Previous researchers (Pusavec et al., 2011) have also proven that cooling conditions play an important role in machining of Inconel 718. This is proven by a significant decrement in the value of surface roughness as shown in Figure 6.

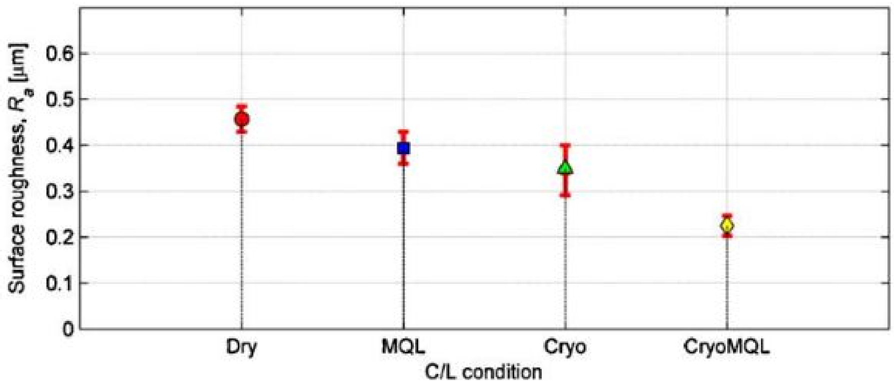


Figure 6: Machined surface roughness for different cooling/lubrication conditions (carbide cutting tool, vc =60m/min, f= 0.05 mm/rev, and ap = 0.63mm)(Pusavec et al., 2011).

4.0 CONCLUSIONS

The effect of machining parameters on cutting temperature, and a comparison of surface roughness in dry and cryogenic cooling cutting conditions for the milling of AISI 4340 alloy steel were carried out. Third Wave AdvantEdge commercial software was used to simulate the cutting temperature distribution contours of dry condition milling process in two dimensions (2D). Average surface roughness for both cryogenic and dry cutting conditions were compared experimentally. The following can be concluded:

(a) Cutting speed is the most influential machining process parameter for the temperature generated during machining.
(b) The surface roughness increases with increase in feed rate. On the other hand, depth of cut has less effect on surface roughness.
(c) The application of LN in cryogenic machining had effectively reduced the average surface roughness.
(d) A 14-24 % average surface roughness decrement in the cryogenic machining, compared to dry milling was observed in the experimental tests.

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