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Experimental Analysis of Milling of Inconel 600 Using Vegetable-Based Cutting Oil with Boric Acid Nano Additives

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Abstract: Inconel 600 is a nickel-chromium alloy, which is suitable for high corrosion and heat resistance applications. This nickel-chromium alloy has outstanding mechanical properties and composes the best workability and high strength combination. Usage of super alloys like Inconel 600 has become a trend nowadays due to the high strength attained with the production of low-weight products. At present days, mostly mineral oils are used while machining to reduce the temperature of the work piece-tool interface. Whereas, the usage of mineral oils causes damage to operators as well as the environment. This mineral oil when exited into the environment it does not get decomposed easily. It also causes respiratory problems to the operators. So, vegetable-based cutting oil can be replaced instead of mineral oil. The present paper deals with such vegetable-based cutting oil and is used for milling Inconel 600 superalloy. Milling experiments were carried out with PVD TiAlN coated carbide inserts in a CNC milling machine. The experiments were conducted with varying speed (1200, 1400, 1600 rpm), feed rate (100, 130, 150 mm/min) and depth of cut (0.15, 0.20, 0.25 mm). Three conditions (dry, wet, wet with additives) were employed. So, a total of 27 experiments were performed. Tool wear and surface roughness were compared for the three conditions. For finding the optimum milling condition Taguchi optimization technique was employed. The vegetable-based cutting oil was added with 1 wt. % boric acid nanoparticles. Tool wear was found best optimal for wet with additives along with 1200 rpm, 100 mm/min, 0.15mm condition. Surface roughness was best suited for wet with additives along with 1400 rpm, 130 mm/min, and 0.20 mm conditions. So, adding nano-additives with coconut oil was found useful as a cutting oil for milling Inconel 600.

Keywords: Inconel 600, Vegetable-based cutting oils, boric acid, nano-additives, coated carbide tools.

I. INTRODUCTION

A group of nickel, nickel-chromium alloys that are used in jet engines and likewise applications are superalloys[1-3]. These metals have very good strength, toughness, heat resistance, and dimensional stability at high temperatures compared to other aerospace materials[4, 5]. They function for a long time at temperatures between 800-1000 °C[6, 7]. Inconel 600 also belongs to that group of superalloys. As the majority of Inconel 600 consists of nickel and chromium, they are extremely corrosion resistant[8-10]. They are also used in applications like heaters, stills, bubble towers, and condensers for processing fatty acids[11-13]. The high nickel content also makes the alloy resistant to chloride-ion stress-corrosion cracking as it resists corrosion by organic and inorganic compounds[14-16]. Inconel 600 however is very hard to machine due to the presence of hard abrasive and carbide compounds, low heat conductivity, and high work hardening[17, 18]. The major problems faced while machining these alloys are tool wear and high heat generation[19-21]. For these applications, special types of coated tools are used as it reduces tool wear and reduces heat generation while machining[22-24]. There is a major problem faced due to chip welding over the tool which is called built-up edge (BUE)[25, 26]. This causes when the heat generated in the cutting zone is high. Getting rid of this problem can be done by using coated tools[27]. In super alloys machining a tool wear monitoring system is well recommended for quality and productivity improvement[28, 29]. So, by a correct tool wear monitoring system, the tool wear rate can be accurately determined and the tool can be replaced in time to avoid the "scrapping" of critical components[30]. During milling, proper selection of parameters plays a vital role. Dry milling of superalloys like Inconel 600 has many disadvantages like high tool wear, low surface finish, and tool face stick[31-33]. Adding cooling oil to the process also plays a vital role and affects the properties of the finished product. Lots of opportunities are opened for vegetable-based cutting fluids as there is a growing demand for biodegradable products[34]. The vegetable oil's molecule is drawn to a metallic surface due to the minor polar charge on the vegetable oil which in turn increases the lubricity of the vegetable oil[35]. The usage of vegetable oil as cutting oil has many advantages as it is biodegradable and does not cause harm to the environment or operator.

Adding boric acid nano additives to coconut oil increase surface finish and reduce tool wear. The 1% wt. boric acid showed better results in coconut oil than 0.5%[36]. Pouring a high amount of lubricants and flooding the workstation seemed to affect the workplace and environment highly and also causes danger to human health[37]. So, adding vegetable oil as a layer on the workpiece is an alternate method of supplying the coolant. Boric acid nano additives were considered to be good green lubricant additive as it is bio-degradable[38]. But dissolving it in vegetable oil is not an easy task, so some alternative methods are to be used for dispersing it in vegetable oil. The present work aims to study the effect of nanoparticle additives in coconut oil on machinability characteristics using coated carbide tools of Inconel 600 in a machine tool. The surface roughness and tool wear characteristics are obtained from the experimental analysis. The results are compared with dry and wet conditions for obtaining the optimal condition for milling of Inconel 600.

II. METHODOLOGY AND EXPERIMENTAL SETUP

In the milling operation, Inconel 600 was used as the workpiece. The chemical composition (wt.%) of Inconel 600 is presented in Table 1. It shows that there is 72 % nickel, 14-17% chromium, and 6-10% iron along with smaller amounts of carbon, manganese, silicon, copper, aluminum, titanium, boron, and phosphorous. The test was carried out with a CNC milling machine as shown in Fig. 1. The Inconel 600 rectangular bar of 75x75x30 mm dimensions was machined with TiAlN coated carbide inserts (XDHT090308PZSRHX WU20PM) which had an insert thickness of 3.18mm.

Table 1. Chemical Composition (wt%) of Inconel 600 alloy.

Element	Ni	Cr	Fe	C	Mn	Si	Cu	Al	Ti	B	P
(%)	72	14-17	6-10	0.05-1.50	1.0	0.5	0.5	0.3	0.3	0.006	0.015

Fig.1. CNC Milling Machine.

A. *Preparation of Nanofluids*

The nanoparticle used in this experiment was Boric Acid (H_3BO_3) which is mixed with coconut oil using an ultrasonicator and magnetic stirrer. The boric acid was bought from *Modern Scientific Co, Coimbatore*. Boric acid is a white powder with a density of 1.435 g/cm^3 at 25 °C. It has a melting point of 170.9 °C. It has been proven that adding boric acid nanoparticles to coconut oil has improved the thermal conductivity of the oil[39]. The boric acid powder was first made into nanoparticle size using a particle sieve as shown in Fig. 2. The boric acid powder was let in the machine for 20 minutes. The mixing ratio was 1% of the nanoparticle to the oil. Mixing nanoparticles in coconut oil is not an easy task as the boric acid does not dissolve in coconut oil easily. So, an ultrasonicator was used to mix the boric acid nanopowder in the coconut oil. A magnetic stirrer was also used to improve the results. The nanopowder of 1 % wt. was added directly to 100 ml of coconut oil and kept in an ultrasonicator for 20 minutes as shown in Fig. 3. The mixture is kept in the magnetic stirrer for another 15 minutes as shown in Fig. 4.

Fig. 2. Particle Sieve.

Fig. 3. Ultrasonicator.

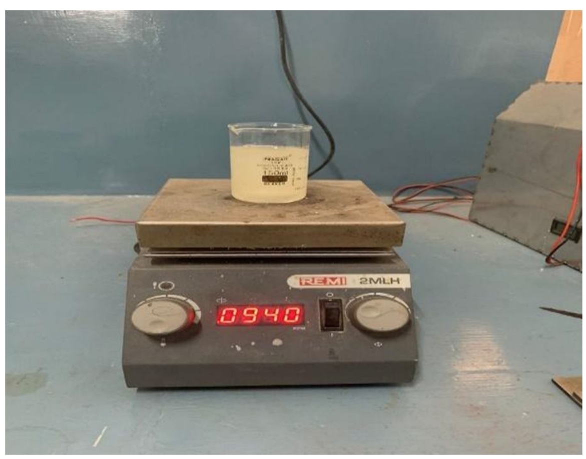

Fig. 4. Magnetic Stirrer.

B. Selection of Parameters Under Taguchi's L9 Orthogonal Array

A total of nine experiments were carried out based on Taguchi's L9 orthogonal array. This reduced the experiment time and the number of tests. The variety of design parameters and combinations used in the test are shown in Table 2. The Signal to Noise (S/N) ratio analysis was done to find the optimal condition for better tool wear and surface roughness using Minitab V20.4 statistical software. The nine experiments were conducted under three different conditions (dry, wet, and wet with additives) for comparing the results to find out the optimal condition for better tool wear and surface roughness.

Table 2. Design Parameters with Levels.

Experiment No.	Parameters	Level		
		1	2	3
1	Spindle speed (rpm)	1200	1400	1600
2	Feed rate (mm/min)	100	130	150
3	Depth of cut (mm)	0.15	0.20	0.25

C. Measurement of Surface Roughness and Tool wear

For measuring surface roughness Mitutoyo SJ-410 Surface Roughness Tester was used as shown in Fig. 5. Mitutoyo SJ-410 Surface Roughness Testers have the ability to do both skidded and skid-less measurements. These SJ-410 series model series provide a wide-range, high-resolution detector and a drive unit that offer high-accuracy measurement in its class. By using the skid-less measurement function ultra-fine steps, straightness and waviness can be obtained[40]. The evaluation range is 25mm. It can vertically travel up to 250mm. It has a measuring force of 4mN. For measuring the tool wear profile projector was used as shown in Fig. 6. A shadow image of the workpiece will be created while the workpiece is placed. The increased image is shown on the screen. This magnification is up to 5 to 100. When an object is placed in between the condenser lens and also the source of illumination, a shadow of the profile is projected at some enlarged scale on the screen. This enlarged profile is going to be compared with the operating normal.

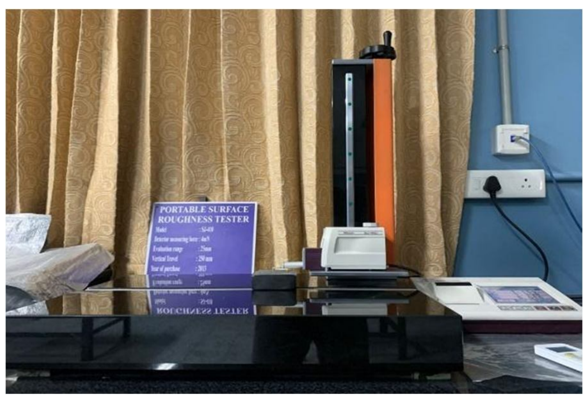

Fig. 5 Surface Roughness Tester.

Fig. 6 Profile Projector.

III. RESULTS AND DISCUSSION

A. *Surface Roughness*

The Surface Roughness Average (Ra) for different spindle speeds, feed rate, and depth of cut for a different combination of vegetable-based cutting oil with and without additives was taken and formulated.

Table 3. Surface Roughness Average (Ra).

Experiment No.	Dry Milling (µm)	Wet (Coconut Oil) (µm)	Wet with Boric acid nano additives(µm)
1.	0.369	0.552	0.707
2.	0.768	0.730	0.457
3.	0.438	0.352	0.645
4.	0.471	0.736	0.487
5.	0.826	0.494	0.214
6.	0.909	1.606	1.156
7.	0.482	0.720	0.324
8.	0.602	0.486	0.301
9.	0.515	0.538	0.924

For the nine combinations of experiments, three different milling process is carried out such as dry, wet, and wet with additives. The values of the surface roughness for the same are depicted in Table 3. Among the dry milling, the least surface roughness value was obtained for Experiment 1 which had the least Spindle speed, Feed Rate, and Depth of Cut values. Experiment 6 got the highest surface roughness value among dry milling during which the depth of cut and feed rate was the highest. So low-speed machining is best suited for the Dry milling of Inconel 600 alloy.

Wet condition is where a layer of coconut oil is poured on the Inconel alloy and it is machined. In that condition Experiment 3 got the lowest Surface Roughness value and Experiment 6 got the highest surface roughness value again. The last combination is milling the Inconel 600 with vegetable oil suspended with nanoboric acid powder. In this again Experiment 6 recorded the highest surface roughness value and Experiment 5 was the least with 0.214 µm. So, comparing all the combinations of vegetable oil with additives proved to be the best for machining conditions with 1400 rpm, 130 mm/min, and 0.20 mm. The highest surface roughness was always obtained in Experiment 6 which hence is not suitable for machining of Inconel 600 alloy.

The Taguchi method is used to find the S/N ratios for comparing the values obtained from the experiments. The S/N ratios widely used are- Nominal is Best (NB), Lower the Better (LB), and Higher the Better (HB). In this present work, Taguchi L9 orthogonal array was used for the experimental design. Minitab V20.4 software was used to design the experiments. The statistical data is plotted in the graph and depicted in Fig. 7.

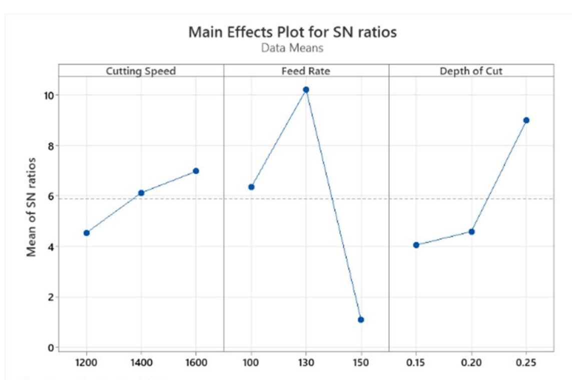

Fig. 7. S/N Ratio Analysis of Surface Roughness for Coconut Oil with Additives.

B. Tool Wear

The tool wear for different spindle speeds, feed rate, and depth of cut. The flank wear is measured in this experiment. The cutting length was kept constant thoughout the experiment. A combination of vegetable-based cutting oil with and without additives was taken and formulated in a table.

Table 4. Tool Wear.

Experiment No.	Dry Milling (mm)	Wet (Coconut Oil) (mm)	Wet with Boric Acid Nano additives(mm)
1.	0.0291	0.0371	0.0286
2.	0.0293	0.0289	0.0305
3.	0.0313	0.0302	0.0299
4.	0.0316	0.0309	0.0328
5.	0.0338	0.0300	0.0316
6.	0.0319	0.0314	0.0324
7.	0.0359	0.0312	0.0316
8.	0.0338	0.0304	0.0311
9.	0.0355	0.0334	0.0301

For the 9 different combinations, three types of milling are employed such as dry, wet, and wet with additives. The average values of tool wear are obtained using the profile projector and are tabulated in Table 4. For the dry condition, the highest average tool wear value is obtained in Experiment 7 and the lowest value is obtained for the lowest design parameters. As of wet conditions where the coconut oil is poured on the Inconel 600 alloy before machining the highest tool wear is obtained for the lowest design parameters value. The lowest tool wear is obtained for Experiment 2. In the wet with additives condition, the lowest value is obtained for the lowest design parameters and the highest value is obtained for Experiment 6.

Overall the highest value is obtained for Dry conditions with high design parameter values. The least tool wear is obtained in wet with additives condition with the lowest design parameter value. On the whole coconut oil with additives of design parameters, 1200 rpm, 100 mm/min and 0.15 mm obtained the least tool wear and was concluded to be the best condition for milling of Inconel 600 concerning the tool wear. The tool wear is also compared with the Taguchi method. The optimum values from the S/N ratio analysis were best for Experiment 5. The values are obtained from the Minitab software. The outcome is plotted in a graph and depicted in Fig. 8.

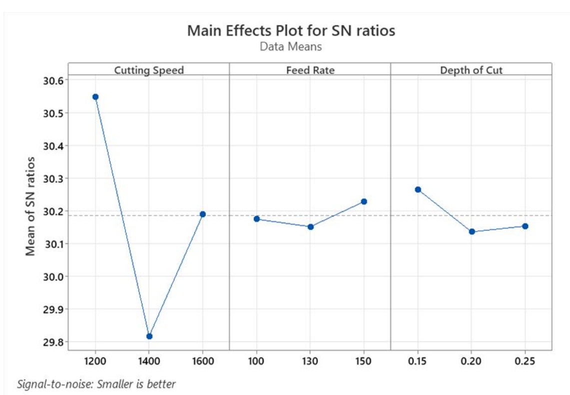

Fig. 8. S/N Ratio Analysis of Tool Wear Coconut Oil with Additives.

IV. CONCLUSION

In this work, Inconel 600 was machined with vegetable-based cutting oil along with nanoparticle (Boric acid) additives. The additives were mixed with the vegetable oil in 1 wt.% concentration. The additive was made to nanoparticle size using Particle Sieve and was mixed using Ultrasonicator and Magnetic Stirrer. The experiments were deliberatively conducted with Taguchi's L9 orthogonal array. The machining parameters such as spindle speed, feed, depth of cut, and responses like surface roughness and flank wear were considered. The S/N ratio for the design parameters was obtained from Minitab software and the graph was plotted. All the experiments were conducted at room temperature. From the experimental results, the following conclusions have arrived:

1) The Surface Roughness was influenced by cutting fluid and additives.
2) The Tool Wear was also influenced by the design parameters and cutting fluids.
3) For obtaining the lowest Surface Roughness coconut oil with 1 wt. % boric acid with 1400 rpm, 130 mm/min, and 0.20 mm design parameters can be used.
4) For obtaining the lowest Tool Wear vegetable oil with additives with low design parameters can be used.
5) Using vegetable oil and adding nanoparticle additives was found to be useful and showed better results.

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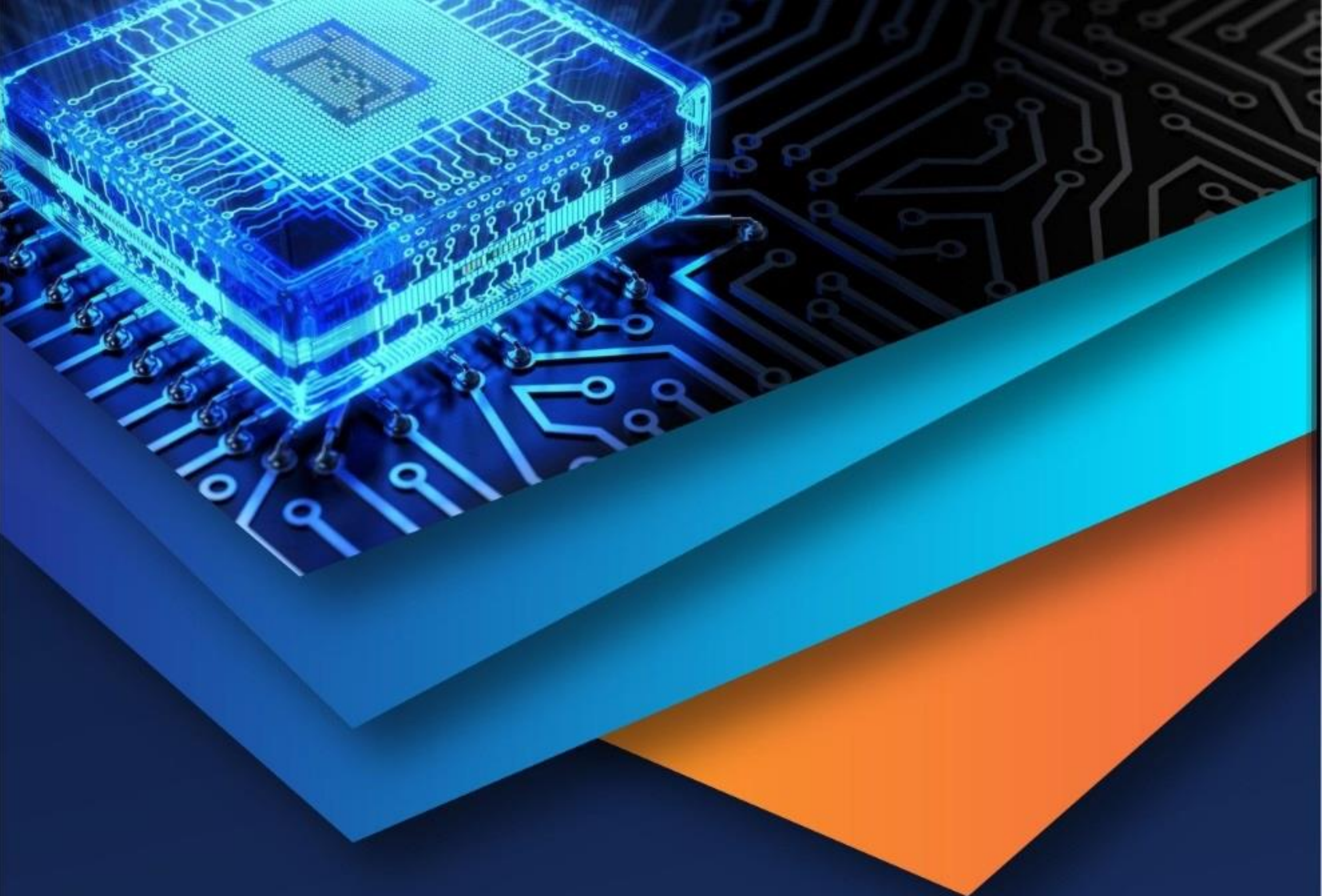

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