Effect of Cutting Parameters on Surface Finish when Turning Nitronic 33 Steel alloy

Vincent A Balogun[*1], Isuamfon F. Edem[2], John Bonney[3], Emmanuel Ezeugwu[4], Paul T. Mativenga[2]

[1]College of Engineering, Department of Mechanical Mechatronics Engineering, Afe Babalola University, Ado Ekiti, Nigeria

[2]School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Manchester M13 9PL, United Kingdom

[3]Faculty of Engineering, Science and the Built Environment, London South Bank University, United Kingdom

[4]Air Force Institute of Technology Kaduna, Nigeria

[*]Corresponding author: E-mail: balogunav@abuad.edu.ng, TEL: +234-803-643-4484

Abstract— Nitronic 33 steel alloys are metallic alloys that exhibit characteristics such as high strength-to-weight ratio, outstanding corrosion and erosion resistant properties, and the ability to withstand cryogenic conditions and elevated temperatures. These characteristics of Nitronic 33 steel alloys make it popular in the fabrication of chemical processing, pollution control, aerospace equipment, and for steam and autoclave applications. Nitronic 33 steel alloy is classified as difficult-to-cut materials because of its high nitrogen content and the capability to form martensite as a result of high temperatures generated during mechanical machining and other subtractive manufacturing processes. This resulted in increased capacity and tooling cost during manufacturing. Therefore, there is the need to evaluate the optimum parameters when machining this alloy for sustainable and resource efficient machining. In this work, tool life, tool wear, surface roughness, cutting forces and power demand when turning Nitronic 33 steel alloy under different cutting environment were investigated. The result presented an optimum turning conditions at which Nitronic 33 steel alloy can be manufactured with minimum tool wear and surface integrity. The research outcome also addresses some of the problems encountered during the high speed machining of Nitronic 33 steel alloy that could influence manufacturing cost reduction. This work will also aid the general understanding of Nitronic 33 steel alloy with respect to sustainable and resource efficient machining.

Index Terms— Austenitic stainless steel, cutting parameters, dry cutting, high pressure cooling, nitronic 33 steel, tool wear characteristics, uncoated carbide tool.

1 INTRODUCTION

Austenitic stainless steels are stainless steel materials which have austenite. They have an FCC (face centered cubic crystal) structure as their primary phase and are mostly resistant to environmental variables. Austenitic stainless steels contain chromium and nickel as the main alloyed elements. They are resistant to chemical reactions (i.e. water, gases, acids, bases, etc) and electrochemical influences of the atmosphere [1]. The austenitic stainless steels also exhibit the work-hardening characteristics which resulted due to the formation of metastable austenite. Hence, unfavourable segmental chips are formed during the mechanical machining processes [2].

Nitronic 33 steel alloy is a nitrogen-strengthened austenitic stainless steel that combines high yield strength with excellent toughness and ductility [3]. The alloy is one of the Johnson–Cook's families of materials [4]. Nitronic 33 steel alloy was reported by Zart [5] to exhibit high resistant to environmental attack regardless of the chemical pollutants and changing environmental conditions. The Armco bulleting [6] also stated that this alloy is aggressive to chemical attacks and has an unchanging functionality at cryogenic temperature ranges. Nitronic 33 steel alloy also has good weldability and low magnetic permeability. These alloys are characterised by high yield strength, high ductility, and endure prolonged lifespan as a result of the high nitrogen content in the chemical composition. Subsequently, and as reported by Douthett [7], they are widely used in the fabrication of various industrial components applicable to the aerospace industries, power generation, chemical processing equipment, bio-medical equipment and applications, defence and armour manufacture, pollution-control equipment, steam and autoclave applications etc. The applications and uses of Nitronic 33 steel alloys were also reported by Milani et al., [4]. Table 1 shows the chemical composition of Nitronic 33 steel alloy.

Table 1: Chemical composition of Nitronic 33 steel alloy adopted from [8]

Alloying element	C	Mn	P	S	Si	Cr	Ni	N	Mo
Weight %	0.041-0.08	11.5-14.5	0.019-0.06	0.005-0.03	0.50-1.0	17.0-19.0	2.25-3.75	0.20-0.40	0.19

1.1 Machinability characteristics of Nitronic 33 steel alloy

From literature, Nitronic 33 steel alloy is classified to be among the difficult-to-cut materials with varying machinability problems. For example Zatz [9] reported that Nitronic 33

steel alloy encourages the formation of built-up edge at the tool-workpiece contact interface during a machining operation. The built-up edge formation allows the chips formed to adhere strongly to the cutting tools during the mechanical machining process. The resultant phenomenon is the fracture and/or plastic deformation of the cutting tool when broken away [10]. In the analysis conducted by Lee et al., [11] to evaluate the magnetic properties of Nitronic 33 steel alloy as an undulator vacuum chamber materials, reported several machinability problems which could affect the linac coherent light source from the material surface. Nitronic 33 steel alloy is of particular interest because of its nonmagnetic properties and wider engineering applications [12]. Nelson [13] reported that during the mechanical machining of Nitronic 33 steel alloy, high level of acoustic emission was recorded. This high level noise can be detrimental to the environment, machine operators and workshop staffs.

In the analysis conducted to investigate the adhesion phenomena in the turning of austenitic stainless steel and carbon steel, Gerth et al., [14] repoted that austenic stainless steel alloys exhibited the difficult-to-cut characteristics. This was attributed to the work hardening phenomenon during the mechanical machining operations and at the same time to the formation of martensite phase (a characteristics common with materials of high nitrogen content) [8]. This phase transformation as a result of work hardening of the material during mechanical machining of austenitic stainless steel alloy resulted to an increase in temperature at the tool-chip contact interface that causes plastic deformation of the cutting tool.

Hosseini et al., [15] reported that high temperature generation at the tool-chip contact interface is a common phenomenon when machining austenitic stainless steel. High temperature generation during mechanical machining is attributable to shorter tool life[16]. Likewise, Saravanan et al., [17] reported that the increase in the cutting force and temperature during an end-milling operation of austenitic steel alloys is essentially due to the iron-chromium-nickel composition of the alloy. A martensitic phase transformation formation is induced as a result of increased cutting temperature. This could increase the tooling cost of machining austenitic stainless steel alloys. Zhu et al., [18] reported that cutting temperature signal analysis is a novel idea that can be used to characterize the tool wear and predict tool wear status especially when machining nickel-based superalloys. Furthermore, during the analysis of the performance of cutting fluids when machining steels, Vieira et al., [19] reported that austenitic stainless steel alloys requires a higher total power demand. This is as result of increased cutting fluid flow due to high temperature at the tool-chip contact interface.

These characteristics exhibited by austenitic stainless steel alloys (i.e. high temperature, built-up edge formation, tool wear, etc) can be adopted to define the economic objectives of machining Nitronic 33 steel alloy (an austenitic stainless steel alloy). Few researchers evaluated optimum machining parameters for machining different austenitic stainless steels. For example Korkut et al., [2] reported that poor surface finish and high tool wear are common phenomenon when machining austenitic stainless steel materials. Juneja and Seth [20] and Gerth et al., [14] reported that work-hardening is attributable to poor machinability of these alloyed steels. Kalpakjian and Schmid [21] reported that cutting forces are higher when machining austenitic steel alloy compared to unalloyed steel as a result of the work-hardening effect encountered during the mechanical machining processes.

Although the cutting and machinability of austenitic stainless steel alloys has been the focus in general, little has been done to investigate the cutting and machinability characteristics of Nitronic 33 steel alloy in particular. Hence, the need to establish optimum cutting conditions for economic and sustainable manufacture of Nitronic 33 steel alloy. This is the focus of this research. This will enhance both the economic and environmental objectives for resource efficient and sustainable manufacture of this alloy. In view of this, the impact of cutting variables on turning Nitronic 33 steel alloy with uncoated carbide tool was investigated. Tool life, tool wear, cutting and feed forces, as well as surface roughness was evaluated.

For the purpose of clarification, the use of proper cutting tool coatings enhances wear behaviour of the cutting inserts, uncoated carbide tools were selected since it has been reported that uncoated carbide tools are also suitable for machining Inconel 718 [22] at sustainable and economic cost criterion. In a recent interview conducted by Diaz et al., [23] they revealed that sales of uncoated tools by RobbJack Corporation (a cutting tool manufacturer) represent 70% of their end mill sales. This shows an increasing trend in the use of uncoated carbide tools within the manufacturing industries. The primary motivations in cutting tool selection are based on the workpiece materials, machining operations and machining economic considerations.

1.2 Aim and objectives

This work is intended to characterise tool life, tool wear and surface finish, cutting force and feed force and power demand during the mechanical machining operations of Nitronic 33 steel alloy. This will enable the evaluation of the optimum turning parameters for resource efficient and sustainable manufacture of this alloy. To achieve this, turning operations were conducted on Nitronic 33 steel alloy with uncoated cutting tool at different cutting speeds and cutting environment. The tool wear were measured and classified in accordance with ISO Standard 3685 [24] for tool life testing.

2 Experimental Setup

The turning tests were carried out on a Colchester Mastiff CNC Lathe which has a manually three-range gearbox and spindle speed output between 18 - 200 rpm, 48 - 605 rpm and 140- 1800 rpm respectively and an 11kW motor drive which can generate a maximum torque of 1,411 Nm. The turning operations were subjected to four different cutting environments i.e. dry, conventional, 7 *MPa* flood pressure and 9.7 *MPa* flood pressure. The workpiece material was Nitronic 33 steel alloy round bar of dimension 293 mm x 350 mm.

The workpiece material was clamped in a three jaw chuck supported with a live centre for adequate support and non-deflection turning. The turning tests were carried out using uncoated insert (SECO Grade 890) CNMG433-MR3-890 incorporating a sintered in the chip breaker grove.

In order to standardise the cutting test, the tool rejection criteria were considered in relation to International Standard Organization, (ISO), 3685 [24] for tool life testing as shown in Table 2. The cutting parameters and cutting environment engaged during the cutting tests were as shown in Table 3 and the experimental setup is as represented in Figure 1.

Table 2: Excessive chipping (flaking) or catastrophic fracture of the cutting edge

Average flank wear (VB) (mm)	≥0.3
Maximum flank wear (VBmax) (mm)	≥0.4
Nose wear (VC) (mm)	≥0.3
Notching at the depth of cut line or tool nose (VN) (mm)	≥0.6
Surface Roughness (Ra) (μ m)	≥1.6

Table 3: Cutting conditions

Cutting speed (*m/min*)	90, 120, 150
Feed rate (*mm/rev*)	0.15
Depth of cut (*mm*)	1.5
Coolant Concentration (%)	6
Coolant supply pressure (*MPa*)	7, 9.7, Conventional and Dry

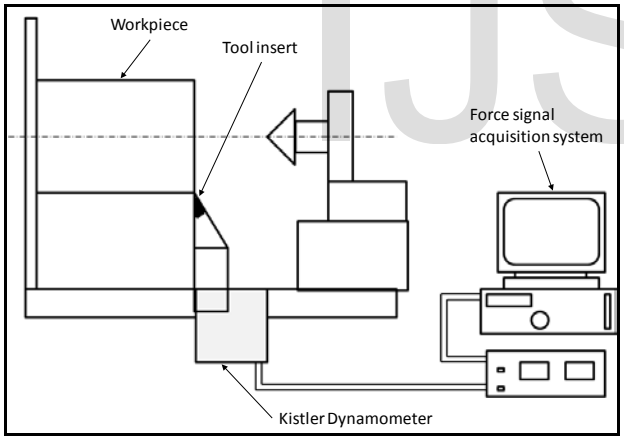

Fig. 1: Machine tool setup

After each turning test, the machine tool was stopped and the cutting tools were examined under the microscope. The tool wear, (flank, nose, and rake face wear); forces (cutting force and feed force) and surface roughness were recorded. The feed rate was maintained at 0.15 m*m/min* and the cutting environment and coolant pressure were varied with different cutting environment (i.e. dry, conventional, 7 and 9.7 *MPa* flood pressure) engaged in turn.

Tool wear was measured with the MITUTOYO Tool Makers Microscope after each turning test. The insert was removed from the tool holder and mounted on the MITUTOYO Tool Makers Microscope for examination. The flank wear, notch wear, and nose wear were measured at a magnification of 25 times using the X and Y coordinates of the microscopes.

The cutting forces were measured using the three-component Kistler piezoelectric tool post Dynamometer and after each turning pass, when the machine tool was stopped, the surface roughness was measured at three different points on the machined surface using a Surtronic-10 (a portable stylus type instrument) measuring device. The stylus travel over the machined surface perpendicular to the machined surface and the relative displacement magnified electronically indicates the surface roughness value (Ra/ m). The measurement was repeated three times for repeatability of data ranges.

After the machining tests, samples of the machined surfaces were collected at different cutting velocity (i.e. 90, 120 and 150 *m/min*) and at different cutting environment (i.e. dry, conventional, 7 *MPa* and 9.7 *MPa* coolant supply). Samples of the rejected cutting tools, based on the tool rejection criteria, for all the given cutting conditions, were also collected. The surfaces of the samples to be examined under the Scanning Electron Microscope (SEM) were etched and cleaned with acetone to remove oil stains, dust and adhering materials. Micrographs of the samples were obtained using Scanning Electron Microscope (SEM), Hitachi S530.

3 Result and Discussions

3.1 Tool life characterisation after machining Nitronic 33 Steel

The relationship between the tool life and cutting speed is shown in Figure 2. It can be seen that as the cutting speed increases, tool life decreases. This trend is as expected since as the cutting speed increases, the cutting tool is subjected to highly localized stresses and high temperatures, which induce tool wear mechanisms and thus adversely affects the tool life, the quality of the machined surface and its dimensional accuracy. There was generally an improved tool life at a cutting speed of 90 *m/min* of 5.167, 3.38, 3.02 and 2.83 minutes for dry, 9.7 *MPa*, 7 *MPa* and conventional cutting environment respectively. Although, Figure 2 shows that turning Nitronic 33 steel alloy under dry cutting environment showed an improved tool life when turning at a cutting speed of 90 *m/min* with uncoated carbide tool insert, the tool life decreases as the cutting speeds were increased to 120 and 150 *m/min* respectively.

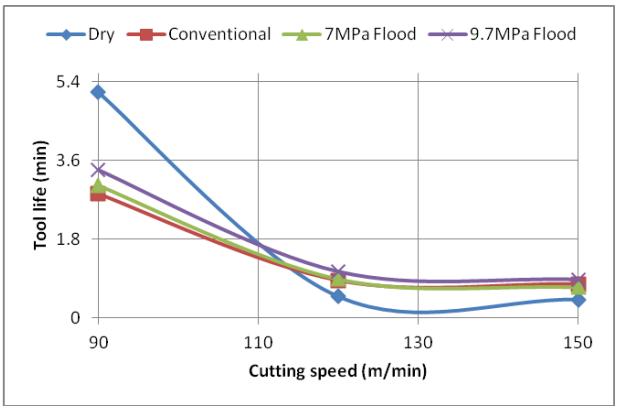

Fig. 2: Variation of Tool Life with cutting speed after machining Nitronic 33 steel with uncoated carbide tool under various cutting environment.

The decrease in tool life is attributable to the increase in temperature within the shear zone thereby causing an induced softening phenomenon at the tool cutting edges. This increases the wear rate of the cutting tool as shown in Figure 3. The conventional, 7 *MPa* and 9.7 *MPa* cutting environment exhibited similar increasing trend of wear rate. The wear rate was 1% of the tool life at 90 *m/min*. This values gradually increases to over 65% for dry cutting environment as the cutting speed increases to 150 *m/min*. An average 30% decrease in wear rate was recorded between dry and cutting with fluids as the cutting speed increases. This is attributable to rapid cooling effect at the tool-chip contact inter phase that encourages the formation of discontinuous chips [25].

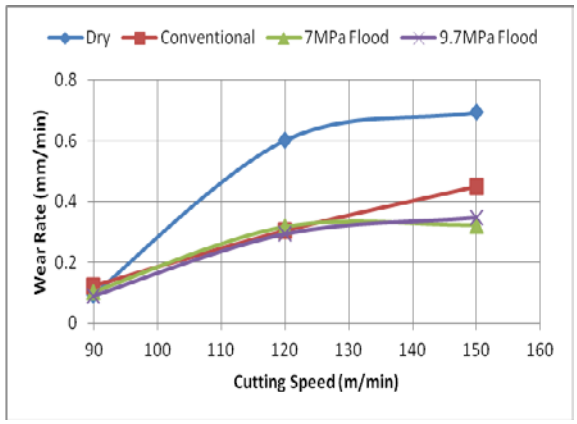

Fig. 3: Wear rate versus Cutting Speed after Machining Nitronic 33 steel with uncoated carbide tool

From Figure 4 and based on the maximum flank wear rejection criterion (Table 2), the cutting insert engaged at 90 *m/min* under dry cutting environment was rejected as the flank wear values exceeded the maximum allowable. However, it took an average of 5 *minutes* to attain the maximum flank wear value of 0.48 *mm*.

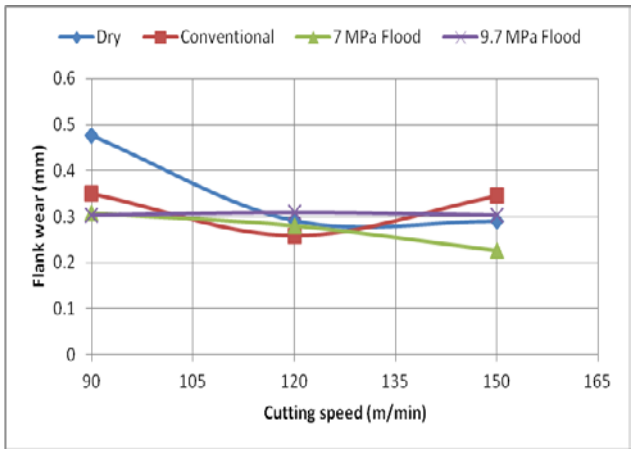

Fig. 4: Flank wear versus cutting speed after machining Nitronic 33 steel with uncoated carbide tool

Nose and flank wear were dominant when machining Nitronic 33 steel alloy as shown in Table 4. These wears progresses under fluid cutting environment as the cutting speed increases during machining. Tool flank wear has been reported to increase when machining at higher cutting speeds but with Nitronic 33 steel alloy, it can be seen that the flank tool wear decreases for dry cutting environment and averagely constant for conventional, 7 *MPa* and 9.7 *MPa* cutting environment within the cutting speeds engaged (see Figure 4). This could be attributable to the formation of a built –up edge welded to the cutting edge of the tool. This tends to protect the cutting edge as the newly welded chip forms a tougher cutting edge of the tool.

Tool damage, either by wear or fracture, deteriorates the surface roughness and accuracy of the machined surfaces. Tool life can be determined based on the size and roughness of machined surface [17]. Tool wear is generally a gradual process. The rate of tool wear depends on cutting tools characteristics and geometry, workpiece materials, cutting environment, cutting conditions and machine tools characteristics [1]. The tool wear observed after turning Nitronic 33 steel alloy are shown in Table 4. The main wear mechanisms observed when machining Nitronic 33 steel alloy with uncoated carbide inserts and at the cutting conditions investigated were; 1) abrasions wear on the rake and flank faces due to hard oxide inclusion, 2) diffusion controlled wear and 3) fatigue wear. It is a common occurrence for several tool wear mechanisms to be active simultaneously and to have a resultant effect on the tool [26]. Flank wear is the dominant tool failure mode in high speed machining [27] and there is no exception when machining Nitronic 33 steel alloy.

Notch wear was also observed as shown in Table 4. This is characterized by excessive localized damage on both the rake and flank face of the insert at the depth-of-cut line. Notch wear is developed due to abrasion caused by work hardening of the workpiece material as it flows past the depth of cut region. This wear is worsened by burr formations especially when machining with uncoated carbide tools.

Tables 4a and 4b are micrographs of uncoated carbide tools after machining Nitronic 33 steel. The micrographs reveals

adherence of the Nitronic 33 steel alloy material to the cutting edge of the tool. This is generally observed in all cutting conditions investigated. It was observed that at 90 *m/min* and under dry cutting environment, the cutting tool shows signs of notch wear at the depth of cut line of the tool as shown in Table 5a. Also, the tool failure mode show both flank and crater wear. The crater wear is marked by smooth wear surface which is a characteristics of thermal wear mechanism such as diffusion wear. However, as the cutting speed increases, material adhesion phenomenon increases even at high pressure flood cooling. These characteristics are common with ductile materials. Generally, the worn tools show that the flank wear developed uniformly during the machining process. Increasing the cutting speed to 150 *m/min* for dry and adopting the conventional coolant method, the dominant wear mechanism was abrasive wear. This is evident by the parallel groves developed at the flank face.

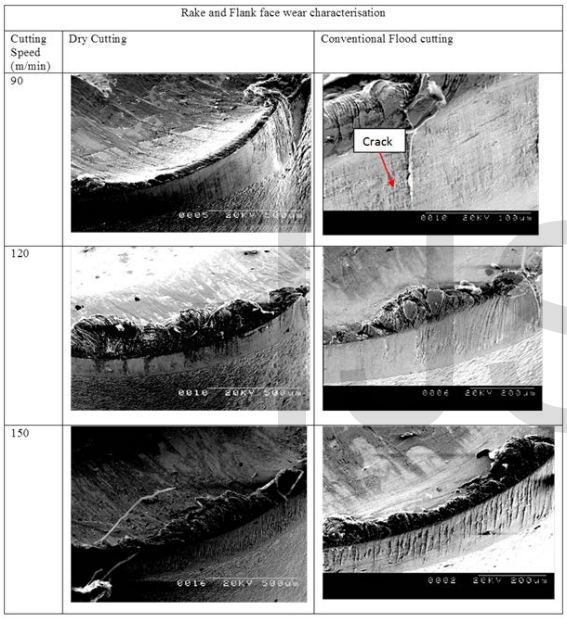

Fig. 4a: Tool Wear Assessment after Machining Nitronic 33 Steel alloy

Table 4a also revealed a crack observed on the flank face of the cutting tool after machining Nitronic 33 steel with uncoated carbide tool at a speed of 90 *m/min* under conventional flood cutting environment. This shows an evidence of high thermal gradient existence at the chip-tool cutting interface during machining which significantly affect the performance of the cutting tool. The uneven rapid cooling induced through the non-contact of the coolant at the tool-chip contact interface led to temperature differences. Similarly, after machining at a speed of 120 *m/min* and under a 7 *MPa* coolant pressure, a pronounced crack developed on the rake face of the uncoated carbide tool. Also, rake face (crater) wear was one of the predominant wear observed when machining Nitronic 33 steel.

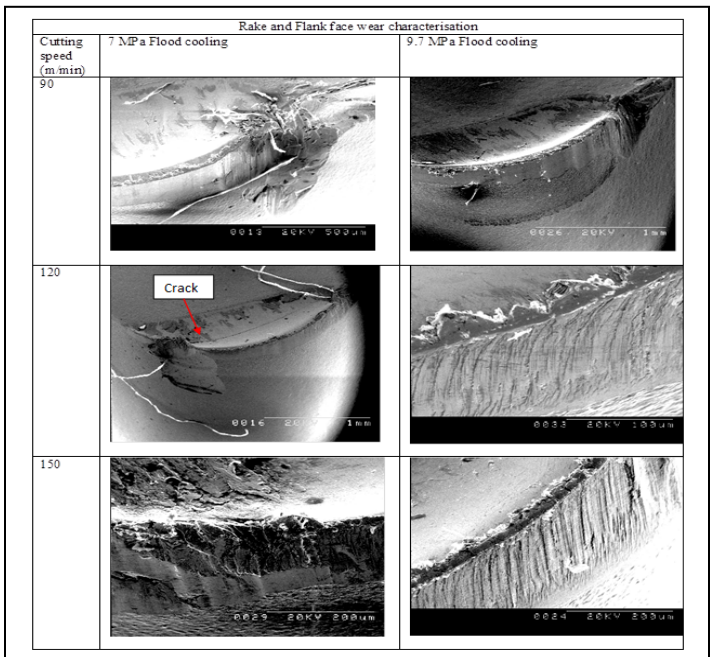

Fig. 4b: Tool Wear Assessment after Machining Nitronic 33 Steel alloy

Tables 4a and 4b shows the rake face wear as recorded in the high speed machining of Nitronic 33 steel alloy. The rake face wear occurred in the form of a pit called the crater, which was formed at some distance from the cutting edge. Experimental results showed that increasing the cutting speed even further led to the increase of the crater wear area. This mode of tool wear is mainly due to high cutting temperature on the rake face as a result of extremely high temperatures (800–1000 °C) occurring at the vicinity of the cutting edge where the depth of crater wear is maximum [28]. The hardness of the cutting tool material decreases at such high cutting temperatures, which aggravates the wear on the tool rake face. High cutting temperature has been reported to accelerate diffusion and adhesion wear as well as plastic deformation of the cutting tool during high speed machining [27]. This is due to the fact that the tool–chip contact length is shorter in high-speed machining than at conventional cutting speed. This is because at high cutting speeds, feed rates are increased and chips formed disengage off the cutting tool faster than the rate at which they are formed. Therefore, the heat generated at the tool-chip interface is transported directly to the cutting tool.

3.2 Surface Roughness and integrity after machining Nitronic 33 alloy steel

Figure 5 shows the relationship between average surface roughness and cutting speeds at the defined feed rate of 0.15 *mm/min* and under different cutting environments. A better surface finish was observed at all cutting conditions (i.e. cutting speed of 90, 120, and 150 *m/min*) as shown in Figure 5. The average surface finish recorded is below the recommended 1.6 µm surface roughness rejection criteria [29]. However, at a cutting speed of 150 *m/min*, and under conventional coolant flow condition, the surface roughness generated was approx-

imately 50% lower than the recorded maximum.

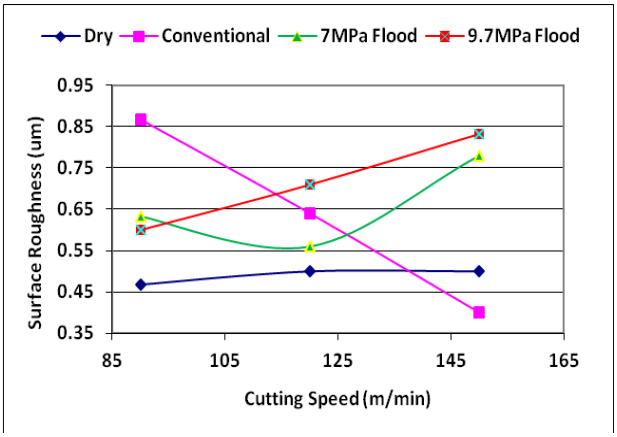

Fig. 5: Average Surface Roughness versus Cutting Speed after Machining Nitronic 33 steel with uncoated under various cutting environment.

Also, it can be observed that the average surface roughness value for dry cutting environment is approximately constant irrespective of the cutting speed employed. An optimum surface roughness is obtained at a cutting speed of 150 *m/min* and under a conventional cutting environment when turning Nitronic 33 steel alloy with uncoated carbide insert. This is evident when the machined surfaces were visualised with the Scanning Electron Microscope (SEM). The samples of the micrographs of the machined surface are shown in Figures 6 and 7.

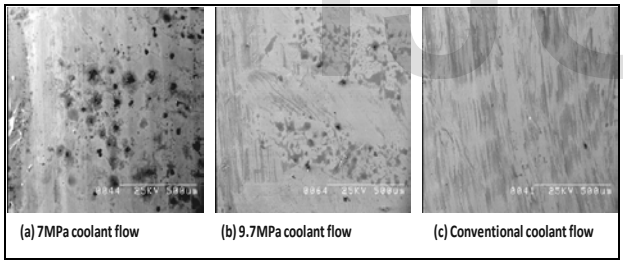

Fig. 6: Micrograph of the machined surface after machining Nitronic 33 steel at speed of 90 m/min magnified x80.

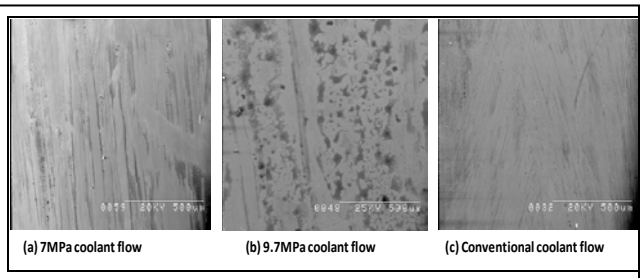

Fig. 7: Micrograph of the machined surface after machining Nitronic 33 steel at speed of 120 *m/min* magnified x80.

From Figures 6 and 7, noticeable black hard inclusion spots are observed. This are hardened material inclusions which could be an area where dislocation of the bonding proves difficult. These hard inclusions could be as a result of the chemical composition of Nitronic 33 steel alloy which for example comprises of chromium, manganese alloy, carbon, etc. Chromium carbides are particularly formed when hard carbides are dispersed in a relatively soft matrix. The alloys forming chromium carbides are particularly effective because these carbides are usually present as relatively large microconstituents, which offer large surface areas to the passage of abrasive material. However, the existence of high content of large chromium carbide makes machining of these hard facings very difficult other than by grinding [30, 31] and/or laser-assisted machining [32]. The manganese composition within the alloy also contributes to the heat resistance of the material and high wear resistance.

3.3 Component Forces after Machining Nitronic 33 Steel

The relationship between the cutting force and feed force with cutting speeds after machining Nitronic 33 steel alloy is as shown in Figures 8 and 9 respectively. The component forces that are generated during mechanical machining could cause high compressive stresses at the tool nose and at the same time plastically deform the cutting tool edge and consequently, would lead to accelerated nose and flank wear rates. From Figures 8 and 9, the feed force ranges between 15-50% of the cutting force at different cutting environment employed.

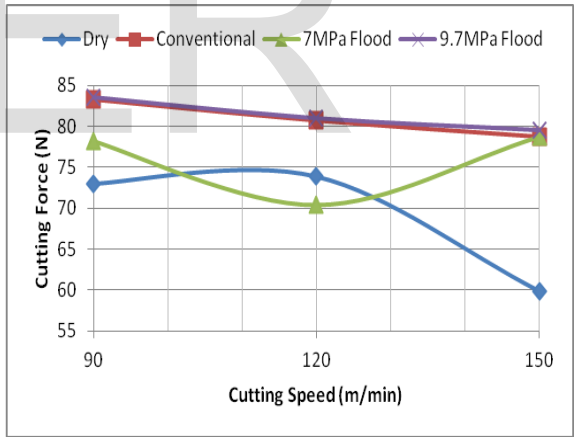

Fig. 8: Cutting Force versus Cutting Speed after Machining Nitronic 33 steel with uncoated carbide tool

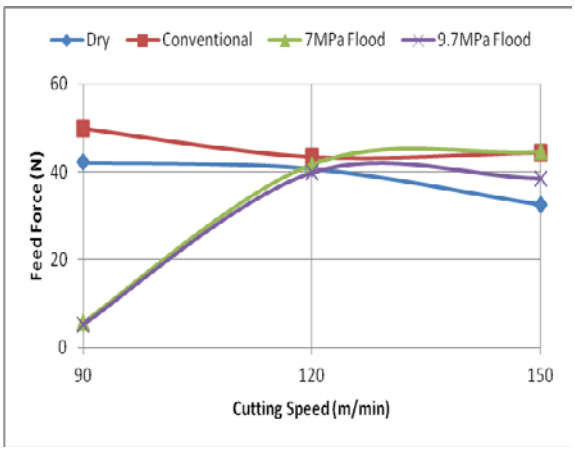

Fig. 9: Feed Force versus Cutting Speed after Machining Nitronic 33 steel with uncoated carbide tool

From Figure 8, higher cutting forces were recorded at a cutting speed of 90 *m/min* (under conventional coolant and 9.7*MPa* coolant flow). Increasing the cutting speed to 150 m/min resulted to a lower cutting force at dry cutting environment while dry cutting environment and 7 *MPa* coolant flow pressure recorded lower cutting forces at 90 *m/min* and 120 m/min respectively.

Figure 9 shows an increasing trend of the feed forces (as the cutting speed increases) at 7 *MPa* and 9.7 *MPa* coolant flow pressure and a decreasing trend for dry and conventional cutting environments. A maximum feed force of 49.87 *N* was recorded at 90 *m/min* under conventional coolant flow condition and a minimum feed force of 5.32 N at 90 *m/min* under 9.7 *MPa* coolant flow condition. Mechanical machining at high pressure coolant supplies resulted to increased feed forces with increasing cutting speed. This is an expected phenomenon and it is attributable to the inability of the coolant to significantly reduce tool temperatures at higher speeds as a result of the conditions of intimate contact, or seizure, that occur over the major part of the chip-tool area. This part of the contact area is not accessible to the water based lubricant (even at high flow pressure) except for minimum quantity lubrication (MQL) through a well defined nozzle angle [33, 34]. Sometimes, it is possible that cutting fluids can slightly penetrate to the friction region at the rear of the tool-chip contact length, and also into the area created by the ragged edge of the chip, these effects do not greatly influence the temperature, cutting forces or tool life at higher speeds [35]. At lower cutting speed conditions, there is the tendency of an increased coefficient of friction. This increases the cutting force and decreases the shear angle. A small shear angle along the shear plane increases the shear plane area thereby increasing the shear force that are required to produce stresses for deformation [25, 36].

3.4 Power Consumption when machining Nitronic 33 steel alloy at high speed conditions

The cutting power was estimated based on the theoretical formula for power demand in machining as in Equation 1.

$$P = \frac{F_c V_c}{60} \quad (1)$$

Where P is the total cutting power demand in *W*, F_c is the cutting force in *N* and V_c represents the cutting velocity in *m/min.*

The variations of cutting power with cutting speed at different cutting environments are shown in Figure 10.

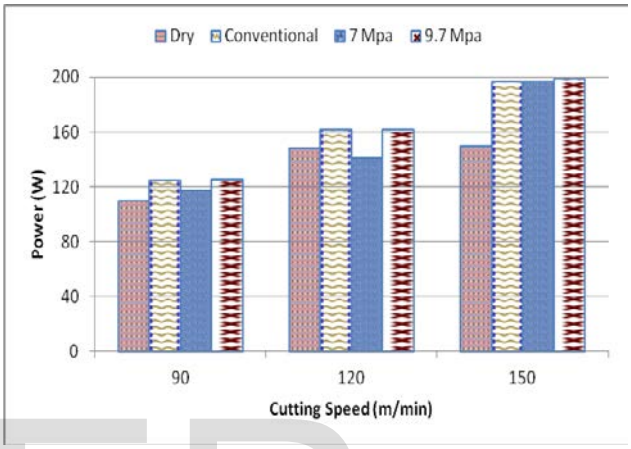

Fig. 10: Cutting power after machining Nitronic 33 steel alloy with uncoated carbide tool

It is clear from Figure 10 that Nitronic 33 steel alloy exhibited minimum power demand at a cutting speed of 90 *m/min* under the dry cutting environment. At this cutting speed (i.e. 90 *m/min*) and from respective sections above, surface roughness and tool life are also at optimum values. The feed force and cutting force can also be said to be at their lowest value for this turning tests when compared to 120 and 150 *m/min* respectively. This further proves that unlike other materials, Nitronic 33 steel alloy materials are better machined at lower cutting speeds and under a dry cutting environment when machining with uncoated carbide tool.

4 Conclusion

This research investigated the cutting variables and their effect on tool life, surface finish, and forces when turning Nitronic 33 steel alloy material. The cutting speed is a fundamental quantity required for the estimation of tool life, wear rates and power demand and can have significant impact on the surface integrity of machined parts. The following conclusions were drawn as a result of this study:

- Rake face wear, flank wear, chipping, and catastrophic tool breakage are the dominant wear patterns throughout the turning process.
- The occurrence of crater and abrasion wear was also noticed on the uncoated carbide insert at coolant flow pressure of 7 *MPa* and 9.7 *MPa* that resulted in the

rake face crack under fluid cutting condition.

- Flank wear showed a maximum at the speed of 150 m/min and higher feed rates increases the tool forces
- It was observed that tool life for uncoated carbide insert under a dry coolant flow condition at a cutting speed of 90 *m/min* was highest at 5.167minutes.
- Notch formation at the depth of cut line was predominant in the machining trials of Nitronic 33 steel
- Material adhesion, crater wear on the rake face and abrasion wear on the flank face are dominant wear modes after the machining of Nitronic 33 steel under the specified cutting conditions. Material adhesion was a constant occurrence throughout the turning tests.
- Crack on the flank face of the uncoated carbide tool was pronounced at a cutting speed of 90 *m/min* and 120 *m/min* under conventional coolant flow condition and 7 *MPa* pressure respectively.
- For sustainable and resource efficient machining of Nitronic 33 steel alloy, it is proposed that a lower cutting speed of 90 *m/min* or less and under a dry cutting environment should be adopted during turning. The tool life and surface roughness exhibited optimum values at 90 *m/min*. This further proves that unlike other materials, Nitronic 33 steel alloy materials are better machined at lower cutting speed and under a dry cutting environment when machining with uncoated carbide tool.

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