Micro features of chips during machining of Incoloy 825 using PVD coated and uncoated carbide tools

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Abstract

Recent decade witnessed a heightened research interest in machining of nickel-based super alloys. This is primarily related to considerable challenge involved in machining of such alloys. Formation of segmented chips caused due to shear localization is a function of cutting environment and has potential to provide further insight into machining of nickel-based super alloys. Therefore, the current study was aimed at evaluation of various chip characteristics under dry machining using PVD multilayer coated tool in comparison with these under traditional flood cooling and minimum quantity lubrication (MQL) while using uncoated tool. Performance of machining for both finish and rough modes has been investigated in terms of chip characteristics such as saw tooth distance, chip segmentation frequency, saw tooth chip angle and segmented length during machining of Incoloy 825. The results showed that coated tool under dry condition resulted in lower value of saw-tooth distance, saw-tooth chip angle, while increase in chip segmentation frequency and chip segmented length in comparison with its uncoated counterpart under wet environment.

Keywords: Incoloy 825, Minimum Quantity Lubrication, Saw Tooth Distance, Chip Segmentation Frequency, Saw Tooth Chip Angle, Chip Segmented Length.

1. INTRODUCTION

Formation of chips plays a pivotal role in the research in machining as it has close interrelationship with cutting force, temperature, machined surface roughness, tool wear etc. Formation of saw-tooth or serration of chip is a relatively common occurrence during machining of difficult-to-cut materials such as nickel-based superalloys, titanium alloys and hardened steels [1, 2]. The chip morphology during machining is not only dependent on tool materials and cutting parameters but others factors like grain size hardness of the workpiece material, use of coolant, geometry has significance influence on types of chips [3-7]. Chip morphology is also influenced by the type of tool coatings which are conventionally deposited using physical vapour deposition (PVD) and chemical vapour deposition (CVD). The chip serration was more prominent when machining of Inconel 718 was carried out with PVD TiN/TiAlN coated inserts compared to that when using CVD coated TiN/Al_2O_3/TiCN carbide tool. This was attributed to the stronger metallurgical bond of CVD coating with cutting tool substrate than that of mechanical bond in case of PVD coatings [7]. Thakur et al. [8, 9] demonstrated that increase in the cutting velocity resulted in decrease in chip thickness, whereas increase in the feed rate caused generation of thicker chips but with reduction in chip compression ratio during machining of Inconel 718. Similarly, increase in the chip-tool contact area also resulted in thicker chip at higher depth of cut [9]. Zhang et al. [10] investigated the influence of cutting speed parameters on types of chips and frequency of chip segmentation during machining Inconel 718. Fine and irregular type of chips were obtained at lower cutting speeds. Two important aspects of chip serration include saw-tooth distance and chip segmentation frequency. These two characteristics of serrated chip are primarily influenced by shear deformation, strain hardening and strain rate. There is no clear agreement among the trend of saw-tooth distance reported by various researchers. Kouadri et al. [13] did not find any clear trend with cutting speed. Wang et al. [14] reported increase in rise in saw-tooth distance with cutting speed, whereas the observation made by Dong et al. [1] was exactly opposite. The frequency of segmentation of saw-tooth type chip decreased with increase in cutting speed. However, the saw-tooth becomes more prominent under the condition of high cutting speed. Dong et al. [1] observed that lower cutting speeds of 20 m/min and 30 m/min resulted in ribbon type chips which gradually transformed to segmented type above cutting speed of 40 m/min at feed rate of 0.1 mm/rev and depth of cut 1 mm during machining of Inconel 718. It was also reported that spacing between chip segments decreased with increase in cutting speed, hence the frequency of serrated chip increased. Furthermore, the frequency of serrated chip initially decreased upto feed rate of 0.16 mm/rev but increased thereafter. Segmented chips were obtained at cutting speed higher than 90 m/min. The degree of chip segmentation was more at higher velocity of 180 m/min with segments being closer than that at lower cutting velocity [11]. Saw-tooth chip angle is influenced by degree of shear deformation, strain hardening and thermal softening [18, 19]. In the feed range of 0.08-0.16 mm/rev the spacing between chip segments increased thereafter it decreased with increase in feed. Pawade et al. [12] studied the influence of cutting parameters and tool geometry on different chip formation characteristics during machining of Inconel 718. Formation of shear band occurs due to thermoplastic instability when the rate of thermal softening exceeds the rate of strain hardening [20-24]. This shear band is responsible for generation of segmented or serrated (also known as shear localised) chips during machining of workpiece materials such as titanium and nickel-based super alloys having low thermal conductivity or those with elevated strength like hardened steel [22].

The review of the past work on chip characteristics of nickel-based super alloys clearly indicated that some study have been reported on effect of cutting parameters on types of chips, macro morphology, chip thickness ratio and characteristics of segmented chips like saw-tooth distance, saw-tooth angle, equivalent chip thickness and chip segmentation frequency. Although different coated tools are frequently used in current industrial practice to machine difficult-to-cut workpiece materials, the potential of coated tools on overall improvement of chip characteristics during machining of Ni- based super

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alloys has hardly been reported. It is, therefore, essential to understand the role of coating on macro and micro morphology of chips and the condition leading to the formation of segmented chips. Incoloy 825 is one of the Ni-based super alloys widely used in aerospace, chemical and marine industries [13, 14]. Although some of the machinability characteristics of Incoloy 825, in particular tool wear and machined surface integrity, have recently been reported [15,16], the detailed chip characteristics of the same material under dry cutting condition has already been published [17]. In the current study, the authors studied the possibility of using best performing coated tools under dry condition in comparison with the uncoated tools under wet environment (flood and MQL). The current study, therefore, aims at micro features of chips during machining of Incoloy 825 using uncoated cemented carbide tool was used under wet and MQL environment, while TiN/TiAlN multilayer coated tool was utilised under dry environment. Different micro features of segmented chips like saw-tooth distance, saw-tooth angle, and chip segmentation frequency of Incoloy 825 have been studied.

2. MATERIALS AND METHODS

During the experiments Incoloy 825 with 75 mm diameter and 650 mm length with chemical compositions of Ni 38 – 46%, Cr 19.5 - 23.5 %, Fe 22 min %, Mo 2.5 - 3.5% , Ti 0.6 - 1.2%, Cu 1.5 3% as workpiece was machined in a heavy duty lathe machine (Make: HMT Ltd., India and model:NH26). Experimental setup of machining of Incoloy 825 is given in Fig.1. Microstructure of the workpiece material has been depicted in Fig. 2, clearly revealing grain boundaries along with precipitation of MC carbides therein. Hard abrasive particles are responsible for worsening overall machinability of Incoloy 825. Machining was performed under roughing and finishing modes of machining as shown in Table 1.

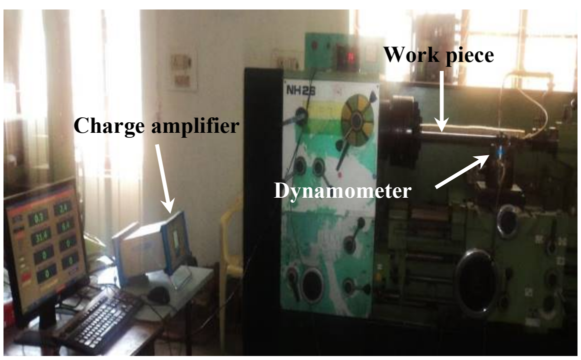

Fig. 1. Experimental setup.

For studying the different characteristics of serrated chips, test specimens were prepared by embedding the chips inside epoxy resin moulds (cold mounting). The specimens were initially polished with different grades of polishing paper having SiC grits. Final surface finish was obtained by etching. The micro-features of the chip's cross section were studied using AxioCam ERc 5s optical microscope (Make: Carl Zeiss).

3. RESULTS AND DISCUSSION

3.1 Chip morphology

Fig. 3 shows a gradual change of macro morphology of chips obtained while roughing and finishing modes of machining. Loose arc and connected arc types of chips were observed with roughing mode of machining owing to high shear strain and plastic deformation as depth of cut and feed both were high. On the other hand, continuous snarled ribbon chips were found with finishing modes of machining. No further variation was revealed with progression of machining. It can be concluded that depth of cut and feed have significant impact on the shape of chip.

Fig. 2. Microstructure of as received Incoloy 825

Table 1 Cutting condition

Cutting tools	• Uncoated ISO K20 grade cemented carbide tool • PVD multilayer coating of TiAlN/TiN
Roughing mode	V_c=51 m/min, f=0.2 mm/rev and a_p=1.5 mm
Finishing mode	V_c=124 m/min, f=0.08 mm/rev and a_p=0.5 mm
Environment	Dry (PVD coated tool), flood (uncoated tool) and MQL (uncoated tool)
MQL supply Air flow rate Quantity of oil consumed Spraying direction of MQL nozzle	Through external nozzle. 0.5 MPa 50 ml/h Rake face
Machining duration	30, 90, 150, 210, 300 and 480 s

Free surface of the chips produced during machining was examined using SEM as shown in Fig. 4. Nickel-based super alloys are usually characterised by serrated chips which are clearly indicated in the same figure for both the modes of machining. Chip serration is primarily attributed to plastic deformation and shear localisation. Higher degree of serration for rough cutting mode might be explained by high feed and depth of cut which caused higher amount of plastic deformation in combination with more chip-tool interface friction compared to finish mode of machining. Degree of serration was also found to be more under dry condition when compared with that under flood and MQL environment. This caused higher amount of deformation energy to be accumulated and subsequently increased shear localisation [25]. Obviously, deformation under wet condition (both flood and MQL) was less. While TiN/TiAlN multilayer coated tool caused easy deformation, it also resisted deformation to the tool itself. This is also indirect evidence of less tool wear for coated tool, since higher tool wear could have caused less cutting deformation which has not been observed for the present case. Prominent side flow of chip material (Fig. 4 a), particularly under flood cooling condition, was due to higher chip-tool interface friction which has been already obtained under finish mode (Fig. 4 b).

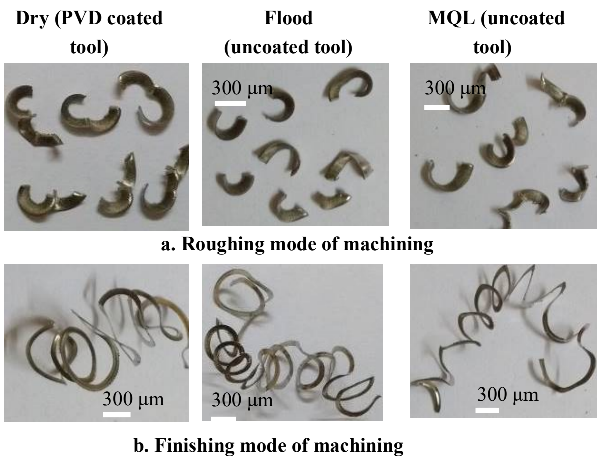

Fig. 3. Optical microscopy images of chips under roughing and finishing modes of machining.

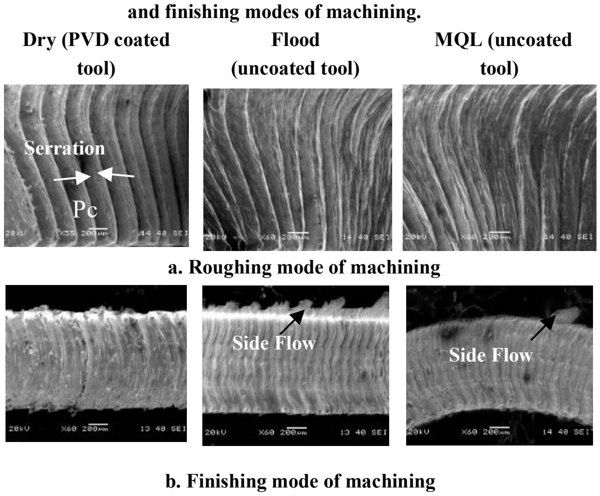

Fig. 4. SEM images of free surface of chips under (a) rough mode and (b) finish mode

3.2 Saw-tooth distance (P_c) and

Saw-tooth distance was calculated from the micro morphology of the chips. Variation of the saw tooth distance in the current study has been shown in Fig. 5 under dry condition using coated tool, under MQL and flood using uncoated tools. Dry machining using PVD coated tool depicts higher value of saw-tooth distance followed by flood and MQL cutting environment. Saw tooth distance is primarily attributed to plastic deformation and shear localisation. Saw tooth distance was found to be more under dry condition than under flood and MQL environment. Owing to higher amount of deformation energy to be accumulated and subsequently increased shear localisation [25]. At the same time, deformation under wet condition (both flood and MQL) was less. Multilayer coated tool caused easy deformation simultaneously reduction in dynamic component of force, it also resisted deformation to the tool itself and less tool wear for coated tool provide uniform saw tooth chip. Uncoated tool suffer from higher tool wear and corresponds to less deformation. Higher value of saw tooth distance for rough mode might be explained by high feed and depth of cut which caused higher amount of plastic deformation in combination with more chip-tool interface friction compared to finish mode of machining. However, no clear trend could be revealed with machining duration. This can be attributed to the occurrence of various competitive phenomenons like formation and removal of built of edge and tool wear. Reduction in saw tooth distance under finish mode could be revealed this might be explain by less formation of built up edge than in roughing mode of machining.

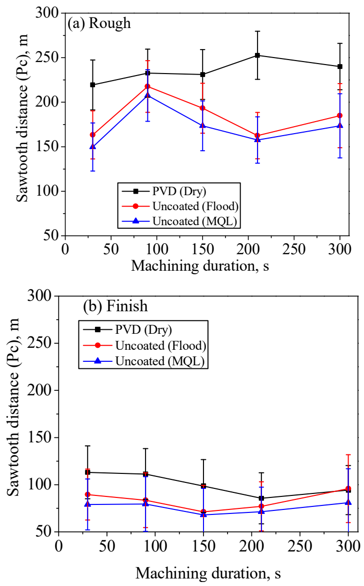

Fig. 5. Variation of saw-tooth distance with machining duration at (a) rough mode and (b) finish mode

3.3 Chip segmentation frequency (f_{ch})

Frequency of chip segmentation was calculated from Eq. (1) [1] where H is maximum thickness of saw tooth chip and γ is principal cutting edge angle.

$$f_{ch} = \frac{V_c f \sin\gamma}{P_c * H} Hz \quad (1)$$

Fig. 6 depicts the effect of cutting environment, machining duration and different modes of machining on chip segmentation frequency. Chip segmentation frequency is dictated by two competing phenomena namely strain hardening or degree of deformation and thermal softening. Chip segmentation frequency observed under dry environment using PVD coated tool is lower than uncoated tool under both (MQL and flood) environment. Increase in chip segmentation frequency might be related to decrease in saw tooth distance. Tool wear plays a major role in decreasing chip segmentation frequency. Tool wear causes plastic deformation in the primary shear zone and large variation in cutting force. A further increase of the flank wear leads to an increase of the chip segmentation. Higher value of chip segmentation frequency for finish mode of machining can be attributed to higher cutting temperature consequently high plastic deformation. No consistent trend of variation of chip segmentation frequency with machining duration could be revealed.

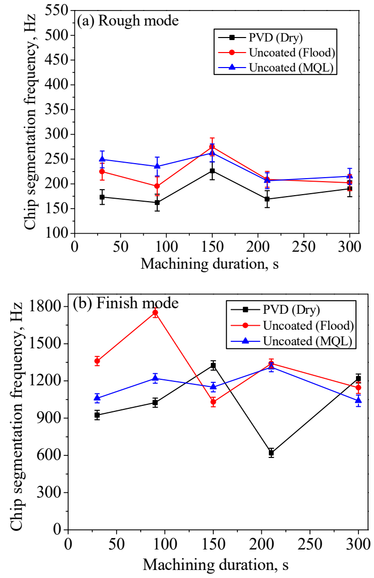

Fig. 6. Variation of chip segmentation frequency with machining duration at (a) rough mode and (b) finish mode

3.4 Saw-tooth chip angle (ϕ_1)

Degree of shear deformation and thermal softening can also be expressed in terms of saw tooth chip angle [25]. Fig. 7 shows variation of saw tooth chip angle using coated (under dry) and uncoated (under both MQL and flood) tools for roughing and finishing modes of machining. The coated tool tends to increase the deformation. It is because of higher strain rate and thermal softening under dry environment therefore, resulted in increase in saw tooth chip angle for PVD coated tool than uncoated one. There is no significant difference in roughing and finishing modes of machining. However, with machining duration decrease in saw tooth chip angle has been noticed.

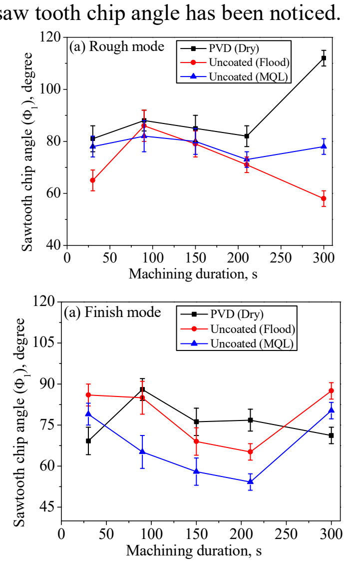

Fig. 7. Variation of saw tooth chip angle with machining duration at (a) rough mode and (b) finish mode

3.5 chip segmented length (L)

Fig. 8 depicts variation of chip segmented length using coated (under dry) and uncoated (under both MQL and flood) tools for roughing and finishing modes of machining. It can be noticed that there is no clear trend with machining duration as well as cutting environmental. However, higher value of chip segmented length under roughing mode of machining whereas lower value in chip segmented length for finishing mode of machining using coated tool. It can be attributed to higher chip tool friction under roughing mode of machining under dry condition than in finish mode of machining.

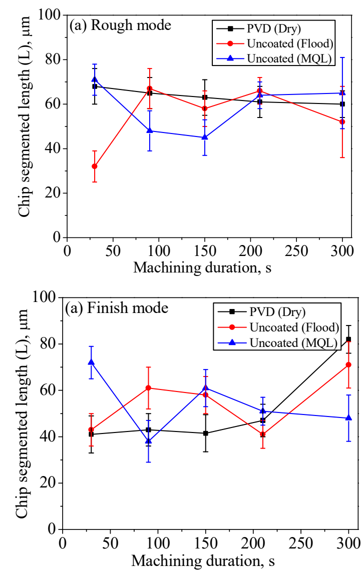

Fig. 8. Variation of chip segmented length with machining duration at (a) rough mode and (b) finish mode

4 CONCLUSIONS

The research work resulted in the following conclusions.

- Use of cutting fluid is more effective in bringing down cutting zone temperature but PVD coated tool owing to its excellent tool wear resistance and antifriction property reduces the fluctuation in cutting force in can be noticed from the formation of saw tooth chip.
- General trend of variation of saw-tooth distance indicated it increased with machining duration. Application of cutting fluid helped in bringing down the saw-tooth distance.
- PVD coated tool has lower value of chip segmentation frequency in both roughing and finishing modes of machining.
- Increase in saw-tooth angle under dry environment using PVD coated tool than uncoated tool.
- However, no clear trend with machining duration and different modes of machining using uncoated and coated tools on chip segmented length.

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