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Effect of cutting speed and tool coating on machined surface integrity of Ni-based super alloy

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Abstract

Inconel 825 belongs to the family of nickel-based super alloy and is widely used in the chemical and marine industry. Although most of the research work was concentrated on machinability of Inconel 718, no such work on the current grade of Inconel 825 has been reported so far. This grade of Inconel is particularly suitable for the applications requiring improved resistance to corrosion. The current study aims at investigating the effect of cutting speed and chemical vapour deposition (CVD) multilayer coating on machined surface integrity of Inconel 825 during dry turning, with particular emphasis on measurement of sub-surface hardness and white layers. Three regions were distinguished beneath the machined surface viz. (a) white layer, (b) plastic deformation region and (c) bulk material. It was observed that increase in cutting speed increased white layer thickness after machining with both uncoated and coated tools. CVD coated cemented carbide insert resulted in decrease in white layer thickness particularly in the lower range of cutting velocity when compared with that obtained by its uncoated counterpart. Vickers microhardness test clearly revealed the work hardening tendency of Inconel 825 with hardness being maximum in the sub-surface region and it decreased when measurements were gradually taken towards the centre of the workpiece. However, this tendency was found to be reduced with the use of multilayer coated tool.

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Keywords: Inconel 825, chemical vapour deposition, microhardness, white layer, field emission scanning electron microscopy;

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1. Introduction

Nickel-based super alloys, owing to their superior mechanical properties, have become an attractive choice of materials in numerous engineering applications. However, these materials pose considerable challenge during machining due to low thermal conductivity, work hardening tendency, chemical affinity and presence of abrasive carbide particles in their microstructure. Surface integrity plays a vital role on the final performance of the machined product. It includes properties of the materials at the surface and sub-surface regions including surface morphology, surface roughness, residual stress, microstructure, and microhardness. During the machining of Nickel-based super alloys, surface defects such as surface drag, material pull out/cracking, feed marks, adhered material particle, debris of chips, surface plucking, deformed grain surface cavities and slip zone were found [1]. Inconel 825 belongs to the family of Ni-based super alloys in which nickel–iron–chromium alloy with titanium, copper and molybdenum are the major constituents. Due to the presence of copper and molybdenum, Inconel 825 possesses the capability to resist corrosive environment. Major applications of Inconel 825 can be found in marine industry, acid production plant, pickling operations, nuclear fuel reprocessing and handling of radioactive wastes and oil and gas recovery [2]. Although extensive research work has been undertaken on the machinability of Inconel 718, not much study on the current grade of Inconel 825 has been reported so far. This is despite the fact that Inconel 825 exhibits much higher resistance to corrosion under hostile environment than that of Inconel 718. Only recently, the authors studied the effect of machining parameters on chip characteristics and tool wear during dry turning of Inconel 825 [3]. Machining parameters play a vital role on machined surface integrity of Inconel 718 [4-9]. Surface integrity characteristics of Inconel 718 with new and worn coated carbide and PCBN

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(polycrystalline cubic boron nitride) tools were analysed. It was observed that machining with new cutting tool resulted in better surface integrity than worn tool for both types of tools. PCBN tool performed better than coated carbide tool particularly at high cutting speed [5].

During machining of Ni-based super alloys, a featureless surface and sub-surface are formed. This featureless region is called white layer. Work hardening tendency of Ni-based super alloys is related to the white layer formation which affects the machined surface integrity. Hard and brittle white layer increases the possibility of crack propagation which in turn has detrimental effect on surface quality and fatigue strength of the machined product [8-13]. However, it has also been observed that thermal softening of the machined surface also takes place at very high temperature resulting in sub-surface region being harder than the top surface [8]. Influence of cutting parameters on white layer thickness during the machining of Inconel 718 has been reported [14]. Hardness of the machined surface and sub-surface region increases with increase in feed as well as cutting speed [8-10].

The current study aims at investigating the effect of cutting speed and CVD multilayer coating on machined surface integrity of Inconel 825 during dry turning operation, with particular emphasis on the measurement of sub-surface hardness and white layers. Variable cutting speeds of (V_c) of 51, 84 and 124 m/min along with constant feed (f) of 0.2 mm/rev and depth of cut (t) of 1 mm were considered during dry turning of Inconel 825. Machining tests were performed with uncoated and CVD multilayer coated (TiN/TiCN/Al_2O_3/ZrCN) cemented carbide inserts.

2. Experimental Methodology

During the experiments, a round bar of Inconel 825 with 75 mm diameter and 195 mm length was machined in a heavy duty lathe machine (make: HMT Ltd., India and model:NH26). Chemical composition of Inconel 825 is provided in Table 1.

Table 1: Chemical composition of Inconel 825

Element	Ni	Fe	Cr	Mo	Cu	Ti
Wt. %	38-46	22 min	19.5-23.5	2.5-3.5	1.53	0.6-0.2

Three different cutting speeds i.e. 51, 84 and 124 m/min along with a constant feed (f) of 0.2 mm/rev and depth of cut (t) of 1 mm were selected during the machining. Uncoated ISO P30 grade cemented carbide insert was used. Its performance was compared with that of an insert with CVD deposited multilayer coating consisting of TiN/TiCN/Al_2O_3/ZrCN arranged from the substrate to top layer. Both uncoated and coated inserts were commercially available tools (make: Widia, India) with ISO insert designation of SCMT 120408. A tool holder with ISO designation of SSBCR2020K12 (Kennametal, India) was used for both uncoated and coated tools. Fig.1 shows photographic view of experimental setup for dry turning of Inconel 825.

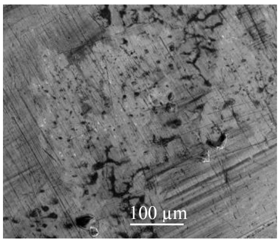
Fig.1 Photograph of experimental setup for turning of Inconel 825.

To measure Vickers microhardness and study the white layers, the machined samples were first cut along the transverse direction containing the plane perpendicular to the axis of rotation and then the cross sectional plane was polished using polishing papers (water proof SiC) with decreasing grit sizes followed by diamond polishing. The polished surfaces were then etched with 2% (by volume) of diluted (40%) hydrofluoric acid, 40% of concentrated hydrochloric acid, 50 % of de-ionised water and 8 % hydrogen per oxide. White layer was studied by observing the surfaces using field emission scanning electron microscopy (FESEM, model: NOVA NANO SEM-450). The average value of white layer thickness was measured by dividing the area (using software of PDF X- change viewer) of the white layer by the length of the SEM micrograph. Five SEM images were captured at different locations of each specimen to improve measurement accuracy. Energy dispersive spectroscopy (EDS) was used to analyse the chemical composition of workpiece material. Vickers microhardness (LECO, USA) was measured on the cross sectional surfaces along a straight line from the edge (corresponding to the circumference of the machined work piece) towards the centre. Each indent was separated from the next one by 20 µm. All the measurement was taken at a load of 0.05 kgf and dwell time of 10 s.

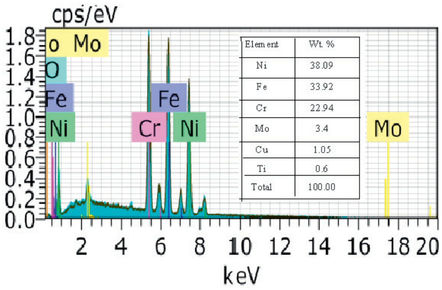
3. Results and Discussion

3.1 Characterization of workpiece before machining

Fig. 2 shows SEM image and corresponding EDS spectrum of Inconel 825 before machining. It can be seen that the chemical composition obtained from EDS has been verified with the standard composition of Inconel 825 provided in Table 1. Fig. 3 shows the image of microstructure of Inconel 825 after etching.



(a)



Element	Wt. %
Ni	38.09
Fe	33.92
Cr	22.94
Mo	3.4
Cu	1.05
Ti	0.6
Total	100.00

(b)

Fig.2 (a) SEM image and (b) corresponding EDS spectrum of as received Inconel 825

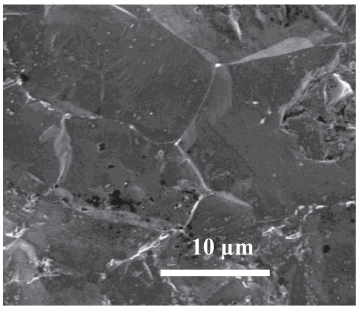


Fig. 3 SEM image of microstructure of Inconel 825 after etching.

3.2 Study of white layer

Formation of white layer during machining is usually dictated by three mechanisms namely plastic flow, rapid heating and quenching and surface reaction [9]. Plastic deformation caused both by mechanical and thermal energy plays a vital role in modifying the microstructure of the workpiece material during machining [1]. Fig.4 demonstrates a typical SEM image of surface and sub-surface region after dry machining of Inconel 825. Three regions can be distinguished from the image such as featureless white layer, plastic deformation region and bulk material. The deformed layer just beneath the white layer might be the consequence of either mechanically or thermally dominated deformation or both depending on the cutting conditions. Fig. 5 shows SEM images of cross section of machined part obtained with different cutting speeds using uncoated and coated carbide inserts. It is evident that as the cutting speed increased, thickness of both white layer as well as deformed layer increased due to the increase in cutting temperature as well more severe shear deformation. Owing to the low thermal conductivity of Inconel 825, heat cannot dissipate to the surroundings quickly. Therefore, the influence became more pronounced with the increase in cutting speed (124 m/min.). Fig.6 shows the variation of white layer thickness with cutting speed for both uncoated and coated inserts. Both Fig. 5 and 6 clearly demonstrate the characteristics of CVD multilayer coated tool over its uncoated counterpart in reducing white layer thickness particularly at low (54 m/min.) and medium (84 m/min.) cutting speed. However, the deformed layer thickness obtained with higher cutting velocity (124 m/min.) was found to be comparable for both uncoated and coated inserts. This phenomenon might be attributed to the fact that Al_2O_3 having low thermal conductivity would not allow heat to penetrate into the inner layers of coating and substrate leading to the formation of thermally affected layer or heat affected zone. The other coating materials like TiN, TiCN and ZrCN, in addition to hardness, possess toughness and impart anti friction properties of the coated tool. Less severity in shear deformation combined with anti-friction properties prevalent during lower cutting speed condition might contribute in reducing white layer thickness using CVD multilayer coated tool.

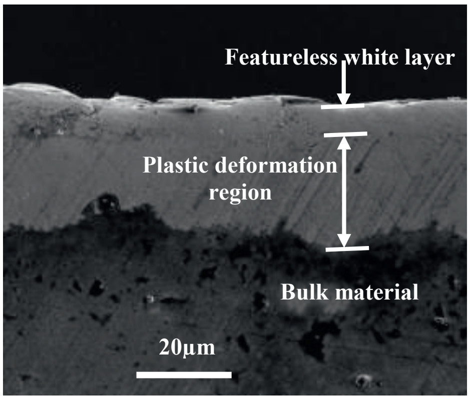


Fig. 4 Representative SEM image of machined surface and sub-surface region

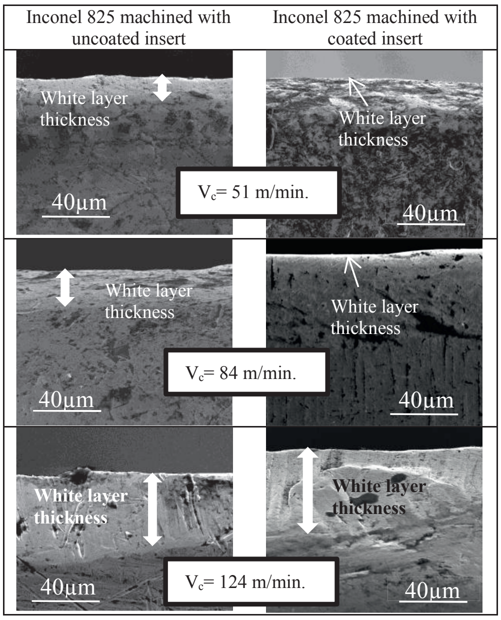


Fig.5 Representative SEM images of cross section of machined part obtained with different cutting speeds.

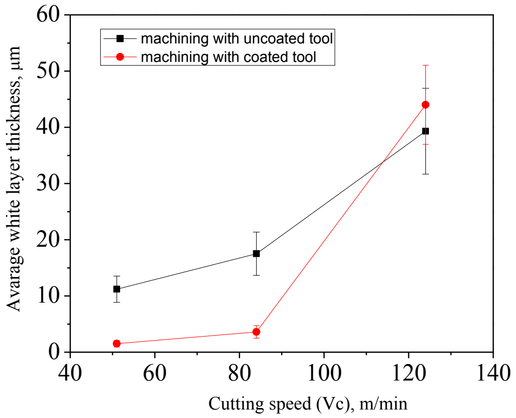
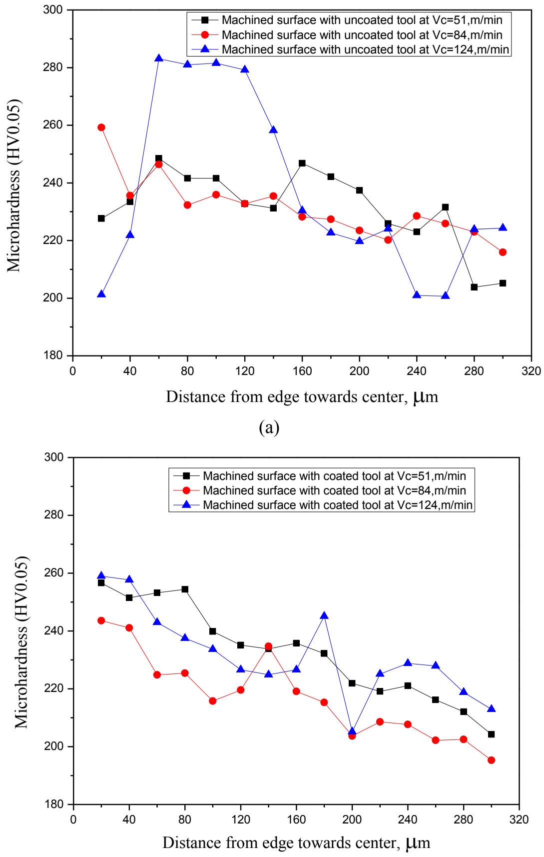


Fig.6 Variation of white layer thickness with cutting speed

3.3 Study of micro hardness

One of the major difficulties associated with machining of Ni-based super alloys includes their work hardening tendency. Therefore, it is essential to investigate the influence of cutting parameters on the degree of work hardening of the machined surface. In the current study, attempt has been made to investigate the effect of cutting speed and CVD multilayer coating on the hardness of the surface and sub-surface layers. Fig.7 shows the variation of micro hardness with distance from the edge towards the centre of machined sample with different cutting speeds (51, 84 and 124 m/min) using uncoated and coated carbide inserts. Two important phenomena can be observed from this figure. First, there is a trend of gradual decrease of microhardness from the machined surface towards the centre leading to the attainment of bulk hardness (200-210 $HV_{0.05}$) of Inconel 825 observed for both uncoated and coated inserts. Second, hardness decreased when the speed was increased from 51 to 84 m/min. However, it increased when speed was further increased to 124 m/min. Fig. 7 also clearly depicts the advantage of coated tool in reducing the work hardening tendency of the machined surface during dry turning of Inconel 825. This observation might be explained by the reduced thickness of the white layer as evident from Fig. 5 and 6. However at low cutting speed (51 m/min) microhardness increased in the sub surface region during the machining with coated tool might be related to the characteristics of the plastic deformation zone that has been formed. Therefore it can be concluded that coated tool could not help in reducing work hardening tendency at low cutting speed. This might be contributed to the general incapability of the coated tool at low cutting speed condition [15]. Fig. 7 further indicates lower value of hardness in the close vicinity of the machined surface while machining with uncoated tool at high cutting speed. This is followed by increase in hardness up to around 280 $HV_{0.05}$ as the depth increases. This might be attributed to the thermal softening associated with higher cutting speed [10-12]. Due to lower thermal conductivity, it would be difficult for the heat to penetrate inside leading to the formation of a kind of mechanically induced deformed layer with higher hardness. Coated tool on the other hand helps to prevent severe escalation of temperature, but at the same time results in a thermally dominated layer (due to lower thermal conductivity of Al_2O_3 coating as explained before) possessing less hardness. Therefore, it may be concluded that CVD multilayer coating has synergistic influence on the improvement of the machined surface integrity-based super alloy (Inconel 825).



(a)

(b)

Fig.7 Variation of micro hardness with distance from edge towards centre of machined sample with different cutting speeds using (a) uncoated (b) coated carbide inserts

4. Conclusions

The current research work investigates the effect of cutting speed and tool coating on machined surface integrity of Inconel 825 with particular emphasis on white layer formation and work hardening phenomena. The following conclusions may be drawn from the study:

1. Three regions have been identified in the machined surface and sub-surface region namely featureless white layer, plastic deformation zone and bulk material.
2. White layer thickness increased with increase in cutting speed.
3. CVD multilayer coated tool exhibited the advantage in reducing the white layer thickness particularly in low and medium cutting speed. However, the white layer thickness was almost similar when machining with high cutting speed with uncoated and coated tool.

4. The microhardness decreased from the machined surface towards the centre of the cross sectional plane, thereby gradually attaining the bulk hardness of Inconel 825.
5. Microhardness first increased and then decreased with increase in cutting speed.
6. Coated tool resulted in reduction in microhardness in the surface and sub-surface region.
7. Thermal softening of machined workpiece was observed at high cutting speed when machining with uncoated tool.
8. Finally, CVD multilayer coating has synergistic influence on the improvement of the machined surface integrity-based super alloy (Inconel 825).

In summary, better surface integrity in terms of white layer thickness and sub-surface hardness can be achieved with CVD multilayer coated tool when it is used for medium (84 m/min) and high (124 m/min) cutting speed.

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