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Performance Evaluation of Coated Carbide Tools in High Speed Turning of Advanced P/M Nickel based Superalloy

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ABSTRACT
Nickel base superalloys processed by the powder metallurgy (P/M) route exhibit improved mechanical properties due to fine-grain homogeneous microstructure over the conventional wrought alloys. The present work demonstrates the performance of an uncoated, single layer and multilayer coated carbide tools in high speed turning operation of advanced P/M nickel based superalloy. The tool performance was evaluated in terms of tool wear, surface finish, diametric deviation and micro hardness. It was observed that tool wear was lowest for multilayer coated tool. The decrease in micro hardness value at machined surface was observed with all variants of tools. The surface roughness was higher with uncoated tool and lower with coated tools. The multilayer coated tool found to be most preferred tool for these superalloys in high cutting speed range (up to 150 m/min). The single layer coated tool can be preferred at intermediate cutting speeds.

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Introduction

Nickel based superalloys exhibit exceptional mechanical properties at elevated temperature which includes high tensile strength, resistance to creep and fatigue etc. therefore these superalloys are extensively used in hot section components of aero-engines. For improved performance, the superalloys composition are tailored to realise high volume fraction of γ'. However, such highly alloyed materials suffer from micro segregation and also prone to cracking in forging operation. In order to overcome these difficulties, processing of high strength superalloys is done through powder metallurgy (P/M) route. The P/M processing imparts fine grains homogeneous microstructure. This results in both inhibition of precipitation of TCP phases and lesser chance of void cracking etc. [1, 2].

In general nickel based superalloys are considerably more difficult to machine than ordinary structural metals and alloys due to low thermal conductivity, poor thermal diffusivity, high rigidity, high toughness, and chemical affinity with tool materials at elevated temperature. The above mentioned properties lead to high cutting forces and temperature, work hardening, high abrasive wear, diffusion of tool and work material, welding/adhesion, tough and continuous chip formation which results in poor surface integrity aspects during machining [3,4]. The machinability index of Inconel 718 found to be around 15-35 as compared to 100 for the free machining low carbon steel [5,6]. This means that machining of Inconel 718 is around 5 to 6 times more difficult than machining of free machining low carbon steel [7].

Veldhuis et. al (2010) had carried out turning experiments on ME16 alloy (P/M nickel based superalloy) with PVD TiAlN coated tools at higher cutting speeds (up to 120 m/min). They observed the formation of thick white layer consisted of γ –Alumina. This acted as a thermal barrier and not permitted the dissipation of heat from the machining zone into the core of work material. This resulted in negative effect on surface integrity and tools life [8].

J. Du et. al (2011) had carried out end milling experiments on FGH95 alloy (P/M nickel based superalloy) with coated carbide tools. The maximum cutting speed used was 65 m/min on which machining temperature generated was 1200°C. They observed that major tool wear mechanisms were abrasive wear, adhesive wear, micro break out and chipping [9].

Yang Qiao et.al (2012) had carried out milling experiments on FGH95 alloy with double layer PVD coated (TiAlN/TiN) carbide tools. They observed the mode of failure as breakage and spalling on the cutting edge of the tool [10].
The selection of the cutting tool material, geometry and coating plays a significant role in improving the machinability of nickel-based superalloys. Cemented carbide cutting tools are the oldest amongst the hard cutting tool materials, which are widely used to machine nickel-based superalloys for intermittent and continuous cutting operations in the speed range of 10–40 m/min from the surface integrity, productivity and economics points of view [11]. The dominant failure modes of carbide tools are severe flank wear and notching at the tool nose and/or depth of cut (DOC). In order to improve productivity by operating at higher cutting speeds, coated cemented carbide tools are used [12]. The use of coated carbide tools produced by the physical vapour deposition (PVD) or chemical vapour deposition (CVD) method has improved the machinability of nickel-based alloys and opened the door to high speed machining at cutting speeds above 50 m/min [13].

A high strength experimental nickel based superalloy of composition comparable to that of the alloy N18 was processed in house through powder metallurgy route involving hot iso-static pressing (HIP) techniques. The HIP alloy was used in the present study as work material to understand its response to machinability with different types of coated carbide tools. The observations noticed

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during the machining experiments are presented in this paper.

Experimental

Test specimens of size 75 mm length and 20 mm diameter were extracted from HIP billet using CNC wire EDM process. The SEM image of microstructure of work material is shown in the fig.1.

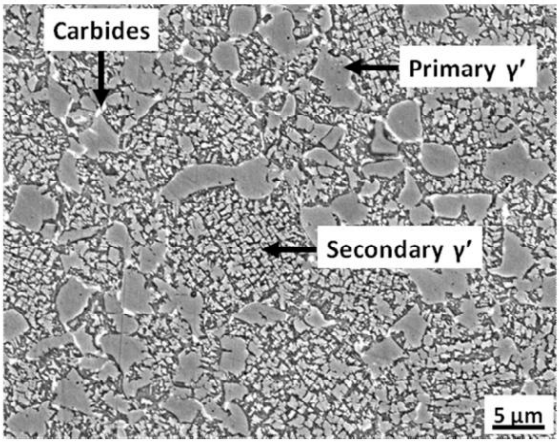

Figure 1: SEM micrograph of as HIPed alloy

The machining experiments were carried out on a CNC Turning Centre (Baitliboi, India make, Sprint 16TC model) of 5.5 KW and 5000 rpm rated capacity. Before each experimental run, the samples were skin cut with required multiple passes at low cutting speed (30m/min), feed (0.04mm/rev) and depth of cut (0.1mm) to achieve true cylindricity. The parameters used in experimentation were cutting speed of 80, 100, 120, and 150 m/min, depth of cut of 0.2 and 0.4 mm and constant feed rate of 0.1 mm/rev under dry cutting environment.

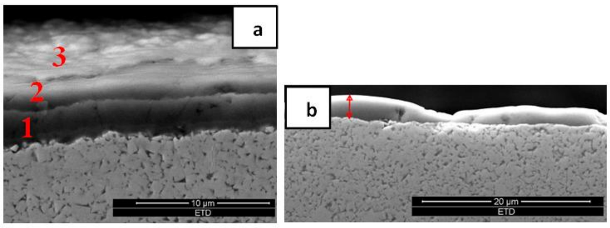

Figure 2: SEM image of (a) Multi-layer (b) Single layer insert

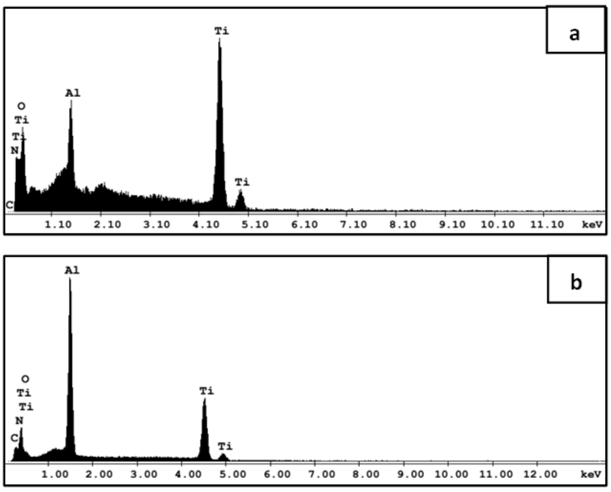

Figure 3: EDS analysis of (a) Multi-layer (b) Single layer coated tool insert

Three different cutting inserts recommended for superalloy machining namely a) Sandvik Coromant make uncoated S grade, H13A insert (excellent bulk toughness). b) WIDIA make WS25PT grade 4-5 µm AlTiN PVD coated (good hot hardness and toughness) and c) Sandvik Coromant make S05F grade, 7-8µm thick triple layer ($TiCN+Al_2O_3+TiN$) CVD coated (excellent hot hardness and flank wear resistance properties) were used. The coatings claimed by OEMs were also verified with SEM images (fig.2) and EDS analysis (fig.3) for coating layer structure and chemical elements present in coating.

The ISO signature of inserts is DNMG with nose radius of 0.4 mm. The tool holder with designation of PDJNL 2020K 15 has been used. The detailed tool holder angles with insert are illustrated in fig.4. The performance of all three cutting inserts was evaluated in terms of tool wear, surface finish, dimensional deviation and machining induced/altered micro hardness.

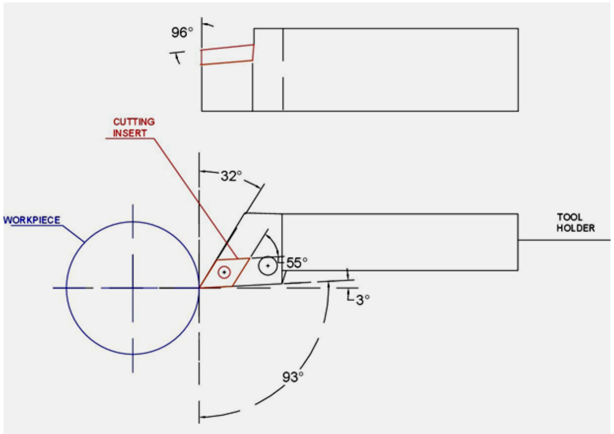

Figure 4: Tool holder angles

Results and Discussion

Tool Wear Analysis

The uncoated (UT), single layer coated (CT) and multi-layer coated (MCT) insert tools were tested for their nose wear aspect for 30, 25, 18, 12 seconds at cutting speed (Vc) of 80, 100, 120 and 150 m/min respectively at 0.2mm and 0.4mm depth of cut (DOC). The value of nose wear has been measured by a Video Measuring Microscope are shown in fig.5. The trend of nose wear is depicted in fig.6.

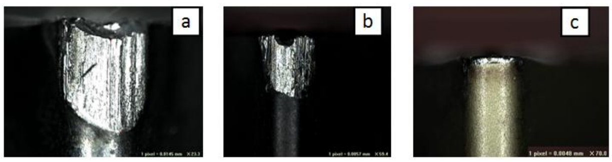

Figure 5: Nose wear of (a) UT, (b) CT and (c) MCT at Vc=100 m/min, f=0.1 mm/rev and DOC=0.4mm

The machining experiments with UT could not be carried out beyond cutting speed of 120 m/min due to premature failure of tool. The acceptable limit for nose wear was considered as 0.4 mm in this study as this value has been used by earlier researchers for superalloys with carbide tools [14]. The nose wear of UT tool has exhibited acceptable at cutting speed of 100 m/min, CT in the cutting rage of 100 –120 m/min at and MCT over the entire range of cutting speeds under low depth of cut (0.2 mm).

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For high depth of cut (0.4 mm) the nose wear of MCT was within acceptable limit over the entire range of cutting speeds. The higher tool life in case of MCT may attributed by multi-functions of the cutting tool, namely, lower friction at the top layer (TiN), thermal protection by intermediate layer (Al_2O_3), and higher wear resistance and stronger adhesion to the substrate by the innermost layer (TiCN). Such tailored performance cannot be achieved by a single PVD coating [15]. The tool tip burning marks and built-up-edge (BUE) formation were observed with UT, flaking of coating was observed with CT and depth-of -cut – notch was observed in case of MCT (fig.7).

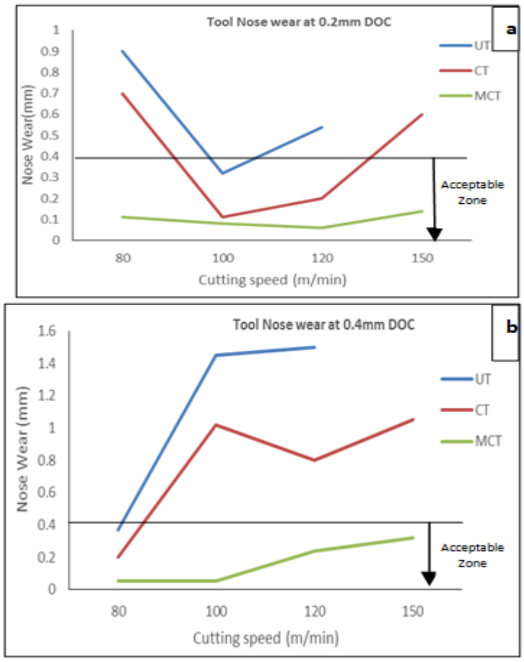

Figure 6: Nose wear trend of UT, CT and MCT with Vc on (a) 0.2mm (b) 0.4mm DOC

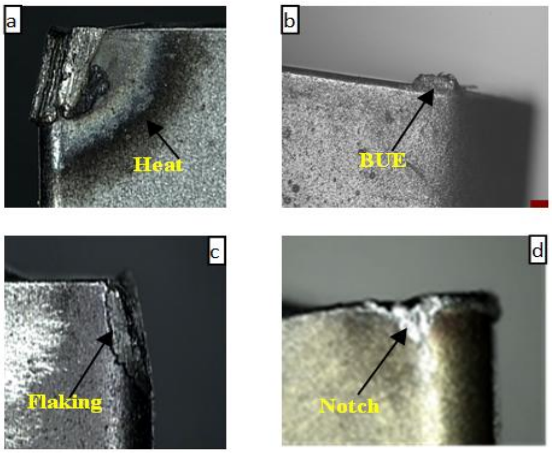

Figure 7: Wear characteristics of (a&b) UT, (c) CT and (d) MCT

Surface Roughness

Surface roughness was measured by a precision roughness tester (Taylor Hobson, Model: Surtronic 3+). The stylus was travelled along the tool feed direction for an evaluation length of 50mm and 0.8 mm cut-off length. Surface roughness in machining is typically depends on several factors such as friction between tool rake-chip interface, formation of BUE, tool wear, tool coating, tool and work thermal conductivity, work material microstructure, cutting temperature etc. [16,17]. Fig.8 shows the variation of surface roughness of work material with cutting speed, depth of cut using uncoated (UT) and different coated CT and MCT tools.

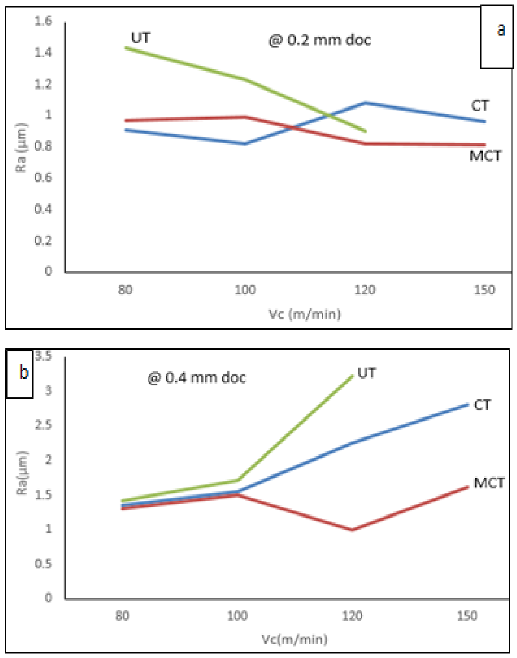

Figure 8: Surface roughness trend of UT, CT & MCT with Vc at (a) 0.2mm DOC and (b) at 0.4mm DOC

It is observed that the value of surface roughness was decreased at higher speed of 120 m/ min for UT. The possible reason may be the increase in temperature due to high coefficient of friction between chip and tool rake surface of uncoated tool. This may reduce the shear strength of work material (softening) and enhance ease in chip formation. The value of roughness was increased with increase of cutting speeds for UT and CT at high depth of cut. The rate of increase is also severe at higher cutting speeds (beyond 100 m/min). The percentage change in surface roughness with increase in cutting speed at 0.2 mm DOC is 20 for MCT, 25 for CT and 37 for UT. At 0.4mm DOC, this change increases to 38% for MCT, 52% for CT and 56% for UT. The best achieved surface roughness with MCT was 0.82µm Ra at Vc of 120 and 150 m/min at 0.2 mm DOC and 1.0 µm Ra with Vc of 120m/min at 0.4mm DOC.

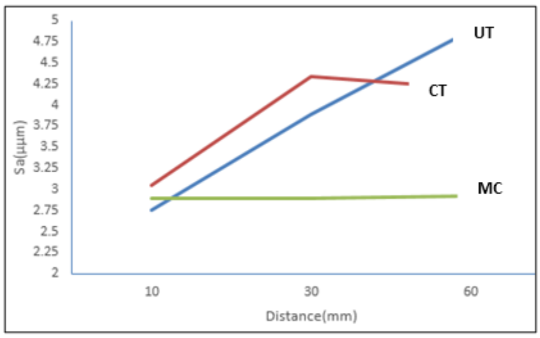

Figure 9: Change in surface roughness with cut length

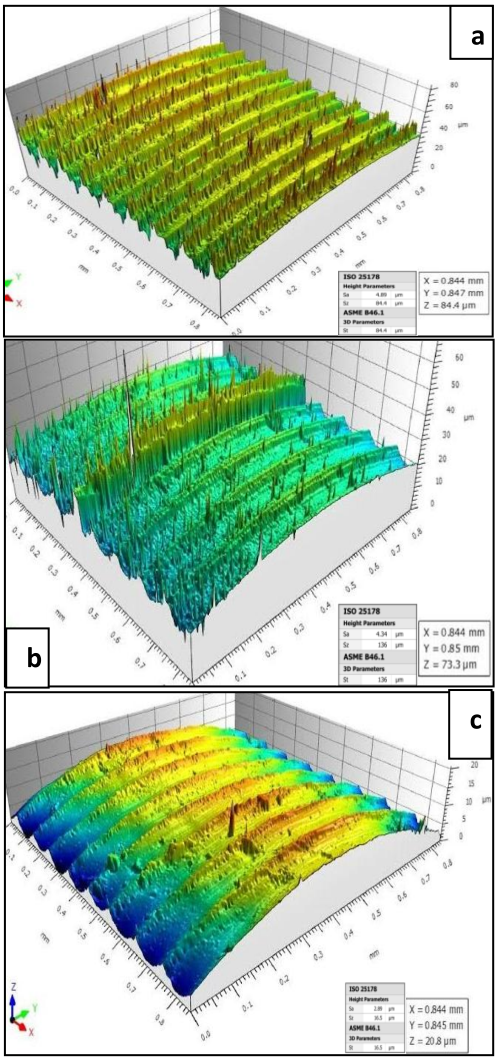

Figure 10: Surface topography of machined work piece surface by (a) UT, (b) CT and (c) MCT

Another set of experiment had been carried out at Vc of 120 m/min, f of 0.1 mm/rev and DOC of 0.4mm to access the change in surface roughness along the length of cut on the sample. The 3D surface roughness (Sa) had been captured in 0.8 x 0.8mm sample size at three places 10, 30 and 60 mm left side from tool entry with the help of Taylor Hobson non-contact surface profilometer. The change in surface roughness trend has illustrated in Fig.9. The surface topography at 50 mm from tool entry side has been depicted in Fig.10.

The trend shows that there was almost no change in surface roughness from entry to exit side with MCT. With CT this difference is recorded to 30% and with UT it was 44%. This infers that tool wear rate is very high in case of UT followed by CT and MCT. Machined surface by UT has more peak density with maximum Sz parameter 84 µm. CT produced less peaks as compared to UT but very high Sz 136µm. MCT generates a well patterned uniform surface with very few abrupt peaks and controlled Sz of maximum 25µm.

Diametric Deviation

After each experimental run the maximum change in diameter (Δd) in machined sample had been measured by a precision micrometer and variations are plotted in fig.11. The diametric variation was within 0.050mm for CT and MCT for entire range of cutting speed at low depth of cut (0.2mm) whereas UT gave maximum variation. At high DOC of 0.4mm, MCT gave lowest diametric variation followed by CT and UT in entire range of cutting speeds.

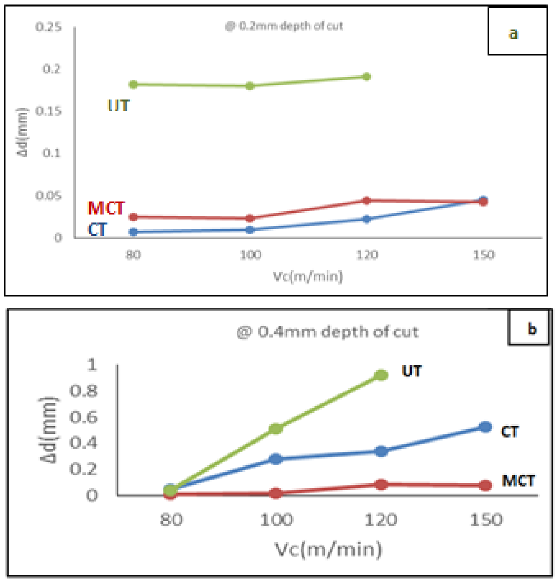

Figure 11: Diametric variation for UT, CT&MCT at a) 0.2 mm DOC and b) 0.4 mm DOC

Micro Hardness Variations

There are many machining induced phenomenon such as lattice distortion, phase transformation, recrystallization, work hardening, change in grain size etc. generally happened within very thin layer [18,19,20]. Many researchers have reported increase in hardness as well as in some cases decrease in hardness also. In this research work the workpiece is machined at two sets of parameters one on which there was no tool wear (Vc 30m/min, f 0.1mm/rev, DOC 0.1mm) happened and another set of parameters (Vc 120m/min, f 0.1mm/rev, DOC 0.4mm) by which tool wear happened. The Vickers micro hardness was measured on the machined surfaces with 50gf load and 10seconds dwell time. The resultant variation in micro hardness has shown in Fig. 11. It indicates that there was a softening effect on the machined by all the tools at both conditions. The uncoated tool (UT) produced maximum softening effect in wear condition (355HV). Whereas multilayer coated (MCT) tool produced least softening effect. Similar softening effect was also reported by Yao et.al (2012) [21] while machining of Inconel718 with grinding process due to phase transformation on the surfaces of work material. It also observed that the percentage change in micro hardness from lower parameter setting to higher parameter setting was minimum of 4 for CT followed by 9 for MCT and 18 for UT.

Conclusions

1. The CVD Multilayer coated tool exhibited highest nose wear resistance than PVD coated single layer tool in machining of P/M Nickel based superalloy at higher cutting speeds.
2. Multilayer coated tool has acceptable nose wear value (0.4 mm) up to the cutting speed of 150 m/min. While

single layer coated tool has in the range of 100 to 120 m/min.

3. The wear mechanism observed in uncoated tools was high temperature burning and BUE formation, flaking and chip-off of coating material in single layer coated tool and depth of cut notch formation in multilayer coated tool.
4. Multilayer coated tool generated lowest surface finish with well uniform patterned machined surface even at higher cutting speed of 150 m/min.
5. Multilayer coated tool had resulted in lowest diametric deviation at high depth of cut values where as single layer coated tool showed better results at low depth of cut values.
6. Decreased values of micro hardness found on machined surface of work material. Higher variation of micro hardness values observed with uncoated tool, but multilayer coated tool showed favorable results.

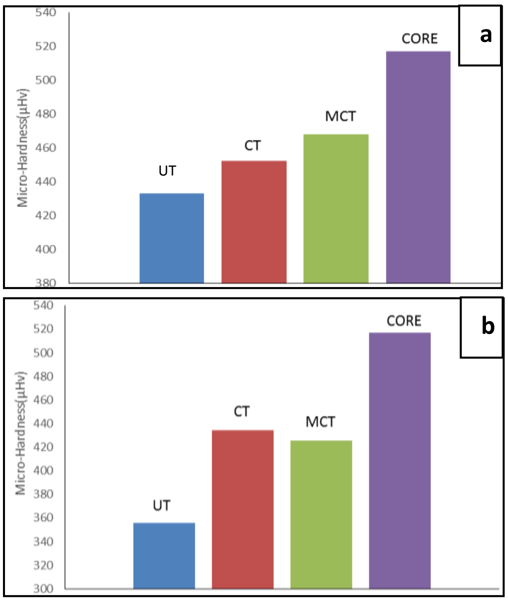

Figure 12: Microhardness values of UT, CT and MCT at (a) no tool wear condition & (b) tool wear condition

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