中國機械工程學刊第三十九卷第二期第 233~244 頁(民國一百零七年)
Journal of the Chinese Society of Mechanical Engineers, Vol.39, No.2, pp 233~244 (2018)

A Study on the Efficacy of Hard Turning (HT) Process in Enhancing the Surface Reliability by White Layer Elimination Using CBN Inserts Under Protective Gas Mixture Atmosphere

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Keywords: Hard turning, Protective gas mixture atmosphere , Super hardened steels, Surface reliability, White Layer

ABSTRACT

Of late, Hard Turning (HT) process has established itself as a feasible alternative to the traditional grinding, due to its ability to facilitate precise machining with better surface finish along with its capability to offer a dry or near dry machining for super hardened steels. However, parts made out of the Hard Turning crops adverse surface pattern known as “White Layer” (WL), which results in poor surface reliability. Hence, this study was focused on the hard turning performed under Argon-CO_2 protective gas mixture atmosphere. Since this gas mixture provides more heat sink at the Thermally Mechanically Affected Zone (TMAZ) during the hard turning process carried out with CBN inserts The innate qualities of this gas mixture excellently curbed the mechanisms which are responsible for the White Layer formation, by ensuring greater heat dissipation by vaporization, regulating uniform cooling through convection and efficiently protecting the machined surface against the environmental reactions. Recently conducted study and their noteworthy results, have for sure established the significant role of this abundantly available and harmless Argon-CO_2 gas mixture, in enhancing the surface reliability by the effective elimination of White Layer formation.

Paper Received. April 2016. Revised, September 2016, Accepted, September 2016, Author for Correspondence: S.Girisankar

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INTRODUCTION

As an improved manufacturing process, and as an innovative machining solution, HT has emerged itself as a viable alternative to the traditional grinding because it enables machining of many intricate profiles in a single set-up. Super hardened steels beyond 45HRC [Bartarya and Choudhury 2012] can be incredibly hard turned by using Dry Machining (DM) or Near Dry Machining (NDM). It is performed by means of the Cubic Boron Nitride (CBN) inserts with or without coatings such as TiN [More et al. 2006]. In this precise machining process, it is possible to machine the super hardened steels, to a very high dimensional accuracy, geometrical and surface tolerances [Girisankar and Omkumar 2015]. The HT is successfully carried out only with the modern machine tools by incorporating sturdiness and stunning tool sliding movements. Though there are many benefits accredited to the HT, it has been found that there are few constraints with respect to the surface reliability properties of the parts produced [Bosheh and Mativenga 2006].

In the actual practice HT usually generates an undesirable surface pattern at the machined surface, due to the phase-transformations popularly called as “White Layer”. This layer has been aptly named after its nature of existence under the microscopic examinations, and it has been considered as an essential surface reliability property. The other surface reliability properties are microstructure, microhardness, chemical compositional changes, surface finish and residual stresses etc… The WL, which forms at the hard turned surface, is about 30% harder than the bulk, and related with the induced tensile residual stress. Whereas the dark layer appears beneath WL is about 60% softer than the bulk related with the induced compressive residual stress [Schwach and Guo 2005]. The dark layers will be exposed after a period of time due to delamination of the WL because of contact stresses. For instance the WL has formed on the bearing races during HT get delaminated due to high contact stresses over a period of time that leads to bearing failure [Bartarya and Choudhury 2012]. Therefore the White Layers are needed to be eliminated not only in the bearings, but also in other parts like press tool punches, dies, pillars, strippers, similarly forging punches, dies, ejectors etc…since it erodes the valuable life of the parts produced. Hence a better machining condition must be devised to enhance the surface reliability, and eliminate WL with compatibility in all respects.

WHITE LAYER FORMATION

The WL formation occurs due to the following three vital mechanisms such as (i) Severe Plastic Deformation (SPD) usually results with very fine homogeneous grain structures, (ii) Phase-transformations due to speedy heating and cooling and (iii) Surface reactions with the atmospheric elements, results in carburizing, oxidizing and nitriding [Bosheh and Mativenga 2006]. The WL occurs due to tool wear from process point of view, and cutting temperature from material point of view, only when the machined surface tends to exceed austenisation temperature and quenched by the atmospheric air thereafter [Schwach and Guo 2005]. And it is to be noted that the cutting speed ranging from 30m/min to 260m/min has been reported as the critical cutting speed that produces maximum depth of WL. This implies that the very high cutting speeds more than 260m/min also generates WL, but with reduced depth of WL due to less contact time result in low cutting temperature, and less prospects for chemical reactions at the machined surface. Basically the HT is a finishing process operated at high cutting speed, low feed and depth of cut. So most of the experiments were conducted as per the critical cutting speed recommended between 100m/min to 250m/min due to stability problems, feed between 0.05mm/rev to 0.2mm/rev and depth of cut not more than 0.2mm [Bartarya and Choudhury 2012].

The following studies were conducted with the recommended machining parameters as cited above, different tool materials, various ceramic coatings on the inserts and cryogenic treating of the inserts. Also machining under DM / NDM / wet / Direct Cryogenic Cooling (DCC) to control the surface reliability problems and WL formation, but that was also result in more surface reliability problems including the WL formation. For instance a performance evaluation shows that a WL with a depth of 2.5μm was formed with dry machining when the cutting speed was 95m/min, feed was 0.06mm/rev and a depth of cut was 0.15mm for TiN coated carbide insert, had a tool wear of 0.2mm after 7min of machining. Then the cutting speed was increased to 180m/min, but the WL with a depth of 4μm was formed for the same feed, depth, wear, time and machining condition. Here it is understood that the increase in the cutting speed generates WL with more depth, also application of ceramic coating was not eliminating WL with its reduced coefficient of friction that prevents tool wear. Further cryogenically treated TiN coated carbide was used; even then the WL was formed with a depth of 1.8μm - 2.9μm for the same parameters, condition, wear and time. Similarly the cryogenically treated uncoated carbide was used, where a WL with a depth of 1.8μm - 2.7μm was formed for the same machining parameters, machining condition, wear and time. So the cryogenic treating of inserts has no role in eliminating the WL even with its improved thermal conductivity and wear resistance.

The WL was also observed with a depth of 2μm - 3μm for the CBN insert with the same parameters, machining condition and time, but the tool wear was measured as 0.14mm due to its greater thermal conductivity and superior wear resistance [Dogra et al. 2011]. Obviously the WL was not eliminated by using different kinds of tool materials, ceramic coatings over the inserts and cryogenic treating of the inserts, whereas they increased the overall processing costs and time. The application of coolants are also known to reduce the WL thickness, but the TMAZ tends to cause the coolants to boil instantly, which in turn deteriorates the tool life, besides badly affects the surface finish by thermal distortions [Zurecki et al. 2003]. Also the coolant residues require fine cleaning after the machining and coolant must be treated well before the disposal. Further the lack of coolant also diminishes the tool life and depreciates the surface finish to an extent [Noorul Haq and Tamizharasan 2006].

Also an experiment was conducted with three distinct machining conditions such as dry (DM) Minimum Quantity of Lubrication (MQL/NDM) and flood cooling (wet). It was observed that the flank wear in DM and MQL was resulting similar for most of the occasions, which was lower than the wet machining [Diniz et al. 2003]. And it was also studied that the MQL exhibits lower cutting force than the wet and dry machining [Wang et al. 2014], but HT will generally produce a low cutting force due to high cutting speed operations [Bosheh and Mativenga 2006, Schwach and Guo 2005]. In another study the DCC (liquid nitrogen) was used to decrease the extreme cutting temperature in order to get improved surface integrity besides reducing the depth of WL over the DM [Umbrello et al. 2012]. Here a CBN insert with a new cutting edge was used for HT, with three different cutting speeds 75m/min, 150m/min, 250m/min and constant feed 0.075mm/rev also constant depth of cut 0.15mm for about 18-20 seconds till the flank wear of the insert has reached 0.03mm to 0.05mm,. But then the application of DCC was also resulting in WL formation with a depth of 1µm, Surely the DCC may be a better option than MQL, DM and wet machining for the HT, since it offers better result with lower tool wear and reduced depth of WL. But it is achieved with an added cost.

Several studies were conducted as stated above to get good surface reliability and to restrict the WL formation as per the recommendations suggested in the earlier studies. Certainly they have reduced the cutting temperature, tool wear and depth of WL, but they were not improving the surface reliability and also generated WL with additional costs, time and pollution. Many approaches were already made with gas based coolants along with the liquid coolants to improve the surface reliability properties. Traditional liquid based coolants have been used in conjunction with gas based coolants such as Air, Argon, Carbon dioxide, Helium and Nitrogen in the form of droplets to enhance their lubrication capability. Moreover Argon, Helium and Nitrogen were used to prevent oxidation over the chips and machined surface.

The following few researches have used different types of gases for cooling, that literally had an effect on the cutting temperature, tool wear, surface roughness and chip morphology. In fact gas coolants have appeared very attractive as far as the penetration problems of the cutting fluids were concerned [Shokrani et al. 2012]. Because the liquid coolants tends to evaporate even before reaching the TMAZ, the reason being that the coolants started boiling rapidly when it contact with the hot machined surface resulting in the formation of a hot vapor film. This intensifies the heat conduction and escalates higher temperature at the machined surface. But then the gas based coolants were able to maintain the cutting temperature well below the softening temperature of the cutting tool materials due to vaporization [Ezugwu 2005]. It was studied that the Nitrogen gas flown at high velocity ejected the chips rapidly, and prevented the removed chips from burning. So this mode of chip removal was not only reduced the cutting force due to lower shear stress but also protected the cutting edge from smudging. It has also reduced the tool wear from the abrasion and adhesion, also improved the surface finish along with chip morphology to get better surface integrity [Ke et al. 2009]. It is also studied that the Argon has allowed the chips to slide smoothly along the insert rake surface, besides prevented the surface reactions and cooled the blazed chips, so that the tool wear and surface integrity have improved [Cristino et al. 2010]. Hence an attempt was made to study the HT process, using CBN insert for super hardened steel under protective gas mixture atmosphere in order to enhance the surface reliability by the WL elimination.

PROTECTIVE GAS MIXTURE

Argon constitutes around 0.93%, whereas Carbon Dioxide (CO_2) represents just 0.03% of the atmospheric air volume and traditionally used with liquid based coolants. Also it is established that the mixture of Argon-CO_2 is non-toxic, non-corrosive, non-ignitable, absolutely inert and heavier than air. Hence these characteristics are much useful in protecting the TMAZ from the effect of chemical reactions, further better heat dissipation with its greater quenching ability. Therefore it can be applied for enhancing the surface reliability properties, and the successful elimination of WL formation. The material compatibility is also adequate as per Part 1: ISO 11114-1 (July- 1998), Part 2: ISO 11114-2 (Mar 2001).

EXPERIMENTAL DETAILS

The workpiece material, cutting insert and machining parameters were selected on the basis of previous studies and it is briefly explained below.

Workpiece Material

The workpiece material taken-up for this study was AISI D2 steel air hardened up to 61-62HRC. Although the other tool steels are available with either improved toughness or wear resistance, AISI D2 cold working tool steel offers the combination of both wear resistance and toughness. So finishing is limited only to regular grinding, also it has extensive usages. So the AISI D2 [Bartarya and Choudhury 2012] steel was selected, and its composition is given in the Table1.

Table1. Composition of AISI D2 steel

Comp	C	Si	Mn	Cr	Mo	V	Fe
%(by wt)	1.5	0.3	0.4	11.8	0.8	0.8	84.34

Cutting Insert

CBN is found to be ideal for HT of ferrous alloys when compared to Poly Crystalline Diamond (PCD). Because at the high temperatures, the PCD inserts partially diffuses the carbon and deposits over the machined surface. Also tends to increase the hardness of the workpiece material, rather than retaining the hot hardness [Galoppi et al. 2006]. So HT by PCD is difficult after carbon diffusion. Hence the CBN inserts have proven to be technologically feasible tool material with its lower tool wear, improved thermal conductivity and inertness than carbide inserts [Dogra et al. 2011]. Therefore the CBN inserts were selected without any additional coating or treating for this study, and the physical properties are given in the Table 2.

Table 2. Physical properties of the CBN

Argon-CO_2 gas mixture

S.No	Properties	Values
1	Hardness	2800HV
2	Tenacity	4.2Mpa
3	Young's Modulus	570Gpa
4	Density	4.3g/cm^3
5	Specific heat	750J/Kg/°C
6	Thermal Conductivity	100 W/m/°K
7	Thermal expansion	4.9X10^-6 mm/°C

The Argon (75%)-CO_2 (25%) gas mixture was selected as mentioned in the section 3, with a purity of 99.9% to provide the protective atmosphere against the environment during the HT. It was stored in a standard gas cylinder near the machine at a safe distance in its natural temperature about 21-23°C. During the HT, it was applied with a single nozzle delivery system, at a pressure of 0.7Mpa [Ke et al. 2009], even though its vapour density was 26% more than the air for better environmental protection. The Argon-CO_2 properties are given in the Table 3.

Table 3. Physical and chemical properties of the Ar-CO_2 as per OSHA, CMA, ANSI and WHMIS

S.No	Description	Properties
1	Color	Colorless
2	Odor	Odorless
3	Density	1.69 g/cm³
4	Vapor density(Air = 1)	1.26
5	Boiling/condensation point)	-185.7°C
6	Melting/freezing point	-189.2°C
7	Critical temperature	-122.4°C
8	Thermal conductivity	0.01735 W/m//°K

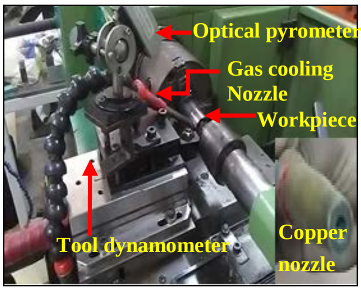
Machining Parameters and Conditions

The machining parameters and the machining conditions are specified in the following Table 4. Moreover the machining parameters were selected on the basis of previous studies, also which were found susceptible to form WL [Bartarya and Choudhury 2012, Dogra et al. 2011, More et al. 2006, Schwach and Guo 2005, Rech and Moisan 2003]. The workpieces of 30mm diameter and 150mm length (l/d<10) were pre-machined and air hardened up to 61HRC - 62HRC. The HT was carried out in the high speed centre lathe GEDEE WEILER MLZ 250V with the cutting temperature and force measurements set-up. The cutting temperatures generated during HT were measured with Williamson optical pyrometer PRO 220-34-C through Pro-view software. It uses IR rays to measure the cutting temperatures from 0°C to 1200°C. Similarly the cutting force components were measured with the Kistler tool dynamometer 9257B from -5KN to 10KN by Dynoware software.

New cutting edges avoids WL formations, hence the semi-worn inserts were selected for this study. So the honed edge semi-worn out inserts of 0.8mm nose radius [Ramesh et al. 2006] with a pre-flank wear [More et al. 2006,Dogra et al. 2011] of 0.2mm ±0.01 (VB_{max}) were selected for HT. Further the maximum pre-flank wear (VB_{max}) 0.2mm has been specified in the ISO3685 as tool life criterion for the HT applications. Hence a low content (50%) CBN, CB7015 grade TNMA160408 TiN coated, 0.015mm honed edge and 0.8mm nose radius with pre-flank wear 0.2mm ±0.01 semi worn-out CBN inserts were selected with a tool holder MTJNL2525M16. The pre-flank wear 0.2mm ±0.01 was induced on the semi-worn out inserts by using them on the dummy workpieces with same properties. Out of six workpieces the three workpieces were hard turned with three individual semi worn-out inserts to a length of 40mm-50mm by without protective gas mixture atmosphere or DM. Similarly the other three workpieces were machined under the protective gas mixture atmosphere.

Table 4. Machining parameters and conditions

S.No	Parameters	Cond. 1	Cond. 2	Cond.3
1	Cutting speed (m/min)	125	187	250
2	Feed(mm/rev)	0.15	0.15	0.15
3	Depth of cut(mm)	0.10	0.10	0.10
4	Pre-flank wear (mm)	0.20	0.20	0.20
5	Machining condition	Dry , gas cooling	Dry , gas cooling	Dry , gas cooling



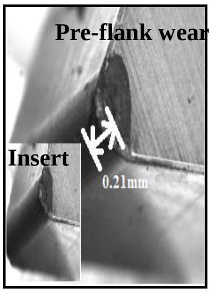


Fig. 1a. HT Machine set-up   Fig. 1b . Insert

The Figure 1a and 1b illustrates machine set-up, and the semi-worn out insert used for the HT. Specimens were prepared from those workpieces, machined with and without the protective gas mixture atmosphere to the appropriate standards; also necessary evaluative tests were carried out to study the resulting surface reliability properties including WL formation.

RESULTS AND DISCUSSION

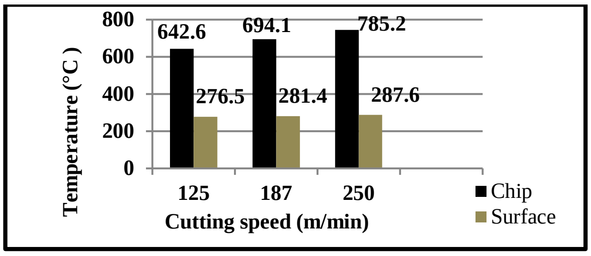
The results obtained regarding the surface reliability properties and also the WL formations are discussed below in detail. It is also understood that the protective gas mixture has significantly ensured compatibility over environment, workpiece material, cutting insert, machine tool and personnel involved.

Thermal impact

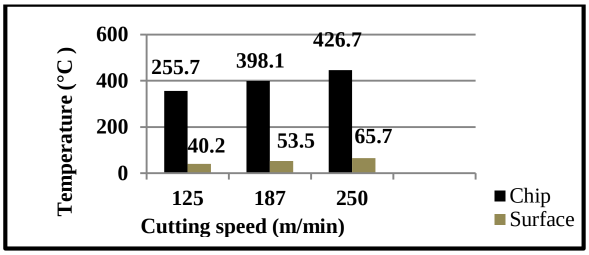
Normally the WL formation during the HT is mainly influenced by the thermal impact due to cutting speed and flank wear [Schwach and Guo 2005, Dogra et al. 2011]. The cutting speed close to higher critical range always generates a very high temperature at the work-tool interface and causes a Dynamic Phase-Transformation (DPT) at the machined surface. And also it produces thermal softening in the cutting tool (insert), as a result it expedites an extreme flank wear at the micro cutting edge. Obviously the thermal impact is one of the dominant factors, which encourages the WL by DPT at the machined surface. Therefore the temperature generated during HT must be lesser than the equicohesive temperature where the strength of the grains and grain boundaries are equal. The fact remains that the grain boundaries will attain the quasi-viscous state at the elevated temperature and the resulting machined surface will be affected by thermal distortions. Subsequently the WL occurs with substantial depth due to thermally driven phase-transformation [Ramesh et al. 2006].

It has been studied that the heat dissipation in DM was inconsistent and this inconsistency was mainly caused by the atmosphere and coolant applied. The cutting temperature at the TMAZ was largely shared by chips removed and the machined surface, whereas the chip and surface temperatures were directly proportional within the range of critical cutting speed [Bosheh and Mativenga 2006]. So the temperatures of the machined surfaces and chips removed under the protective gas mixture machining and DM were measured and compared for the thermal impact. The gas based coolants appeared very attractive as far as the penetration problems of the cutting fluids were concerned [Shokrani et al. 2012]. And competent enough to maintain the cutting temperature well below the softening temperature of the tool materials [Ezugwu 2005]. The lower thermal conductivity of cutting tool tends to reduce the depth of WL [Aramcharoen and Mativenga 2008]. But CBN insert has more thermal conductivity, so it results in greater thermal impact, but the Argon-CO_2 gas mixture was able to reduce the effect by its low thermal conductivity, which was 32% lower than the atmospheric air.

In addition to the lower thermal conductivity, the heat was dissipated effectively by vaporization with its low boiling point. Thus it yielded a very low temperature at the machined surfaces, which was so close to the ambient temperature [Ke et al. 2009]. The Figure 2a and 2b illustrates the average temperatures measured from the chips removed and surfaces machined with and without the protective gas mixture at three different cutting speeds as specified in the Table 4. The difference between the mean cutting temperatures for the chips removed, with protective gas and without the protective gas machining are noticed from 296.0°C to 386.9°C. Also the difference between the mean cutting temperatures at the surfaces machined is found to be from 221.9°C to 236.3°C.



a. Without protective gas mixture

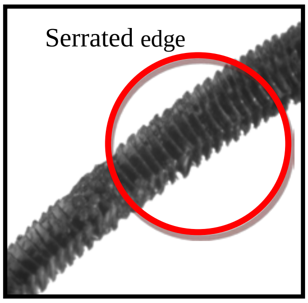


b. With protective gas mixture

Fig. 2. Mean temperatures measured from the chips removed and surfaces machined

It is witnessed that the chips temperature under protective gas mixture has fallen below [Cristino et al. 2010] the austenite temperature 730°C; similarly the temperature of the surfaces machined under protective gas mixture was also controlled well below the low temperature tempering range between 150°C-250°C. During DM, the chip temperature was noticed twice more than the temperature of the surface machined at high cutting speeds [Aramcharoen and Mativenga 2008]. Here the average temperature ratio between the chips removed and the surfaces machined for without protective gas mixture /DM is noticed between 2.31 to 2.73 times, but under the protective gas mixture it is noticed from 6.36 to 7.44 times. This shows that the gas mixture has shared a substantial heat along with chip, tool and surface machined.

Obviously it is evident that the effect of thermal softening in the primary deformation zone was higher than the secondary zone and led a plastic instability in the machined surface during the HT with DM. This phenomenon has induced a higher thermal stress, along the shear plane and produced serrated chip morphology [Ke et al. 2009]. It is supported by the image taken by Bluecougher X125 camera with 2X inline Telecentric lens. For instance the Figure 3a has shown a burnt, serrated edge and continuous bluish chip obtained during without the protective gas mixture machining / DM, but the Figure 3b shows an unburnt, continuous edge and fragmented grayish chip produced by the lower thermal stress induced under the protective gas mixture. Also the same chip morphology were noticed for the chips produced with other cutting speeds.



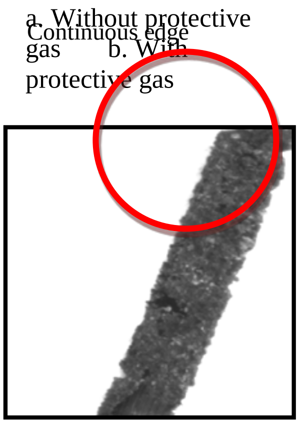


Fig. 3. Chip morphology for the cutting speed 187m/min

Surface roughness

Actually the surface roughness is the first aspect of the surface reliability properties and it is recognized after machining the component. The surface roughness (Ra) was measured by a 3D non-contact surface roughness tester with a cut-off length 0.8mm at an orientation 120° circumferentially without any interference at three different points [Dogra et al. 2011], and then the mean values were obtained for each specimen as shown in the Fig. 4. The low thermal stress induced by the protective gas mixture machining significantly maintains excellent cutting edge integrity and protects the micro cutting edge of the inserts free from flank wear [Ezugwu 2005]. Also the speedy ejection of the gas mixture averted adhesion between the blazed chip and insert, which further minimized abrasion over the surface machined, thus an appreciable surface finish was obtained [Ke et al. 2009].

Figure 4 illustrates the mean surface roughness obtained for the surfaces machined without and with the protective gas mixture machining at the three different cutting speeds as specified in the Table 4. It is noticed that the surface roughness decreases with increasing cutting speed [Umbrello et al. 2012], since the abrasion and plowing effect reduced significantly with increase in the cutting speed. The surface roughness obtained under without protective gas mixture machining/DM is noticed considerably more for low cutting speed due to more abrasion and plowing effect, but almost same for the medium and high cutting speed due to reduced plowing effect. Whereas the surface roughness obtained under protective gas mixture machining is noticed as same for all the three cutting speeds due to negligible abrasion and plowing effect. Certainly the roughness achieved for both the surfaces were significantly lower than the conventional grinding process where the least possible surface roughness achieved was 1.6μm [More et al. 2006]. By grinding Al_2O_3 ceramic wheel, the best surface finish achieved after 5 passes with water soluble emulsion was 0.27μm [Grzesik et al. 2014]. Evidently it is found that the surface roughness achieved under protective gas mixture machining was remarkably better, by which it can very well replace grinding process [Umbrello et al.2012].

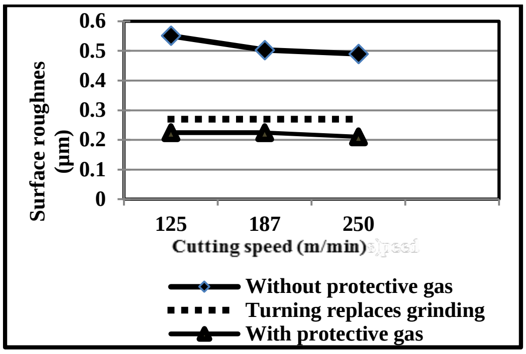
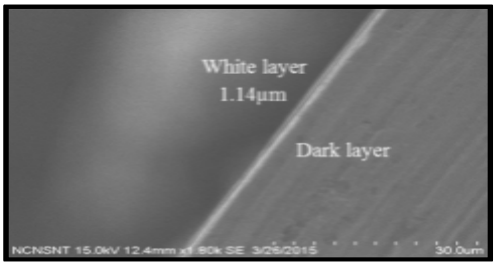


Fig. 4. Mean surface roughness

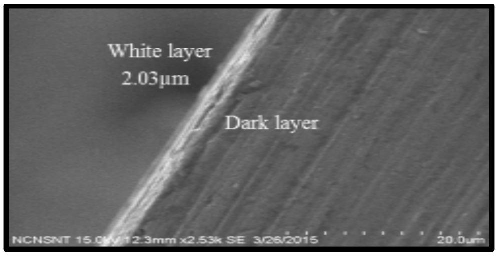
White Layer formation

Generally the critical cutting speed from 30m/min to 260m/min and minimum flank wear above 0.025mm increases the cutting temperature at the machined surface, so they are mainly responsible for the WL formation. It was also observed that the low to moderate critical cutting speeds tends to cause a mechanically driven phase-transformation where the material is sheared away intensively, and generates SPD. The higher critical cutting speed tends to cause a higher heat concentration, thus it encourages greater thermal stress and induces thermally driven phase-transformation [Ramesh et al. 2006]. But both phase-transformations tends to crop a disturbed surface pattern known as WL. The cutting temperature generated at the TMAZ reaches to the austenitic range at the machined surface. Therefore the WL consists of partially transformed fine martensite and small amount of retained austenite. Consequently the depth of WL formation seems to be increasing with the increase in critical cutting speed [Dogra et al. 2011, Umbrello et al. 2012]. Also it is observed that the depth of WL varies over the entire length of the surface machined, because the semi-worn out inserts are limited to side flow free region [Bushlya et al. 2011]. Therefore the WL formation and the subsequent thickness intensification are influenced by the extreme thermal impact and excessive tool wear.

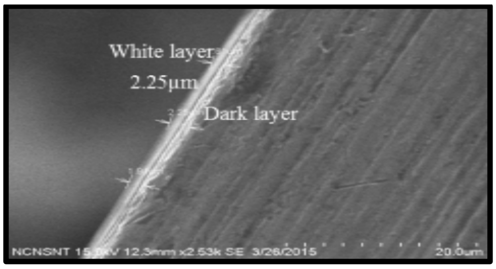
The SEM images taken for the surfaces machined without the protective gas mixture/DM are illustrated in the Figure 5a, 5b and 5c. It visibly shows the WL at the machined surfaces by the intense localized rapid thermo-mechanical action. It is evident that the semi worn-out inserts used and higher cutting temperatures generated have produced a continuous WL with an average thickness of 1.14μm to 2.25μm for the three different cutting speeds. The WL was formed predominantly due to the mechanically driven phase-transformation at the low cutting speed 125m/min. So the average thickness of 1.14μm was noticed due to lower heat impact, but maximum depth was produced around 2.03µm, 2.25µm at high cutting speeds 187m/min and 250m/min. It is observed that the WL was formed predominantly due to thermally driven phase-transformation, since the temperature was very much closer to the stable austenitic range. Also the dark layers were observed with severe plastic strain due to the induced tensile residual stresses.



a. (v=125m/min, WL=1.14µm)



b. (v=187m/min, WL= 2.03µm)



c. (v=250m/min, WL= 2.25µm)

Fig. 5. Surfaces machined without the protective gas mixture

To substantiate the WL formation, halcon coding was developed with image processing software *HDevelop* for the surface machined without protective gas mixture at the cutting speed 187m/min. The Pseudo colour images with auto-threshold gray values are illustrated in the Figure 6a and 6b. These gray values were obtained for the regions such as bulk, WL and environment in terms of gray_ min/max/mean. It also shows those regions in three different colours namely green, purple and red. As shown in the Fig 6a the gray_mean values of WL region are greater than bulk region by 1.95 times.

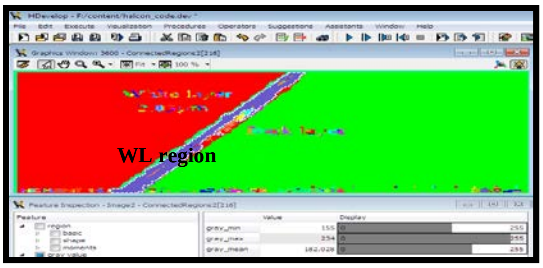


Fig. 6a. Pseudo colour image with auto-threshold values of WL region for the surface machined without protective gas mixture at the cutting speed 187m/min

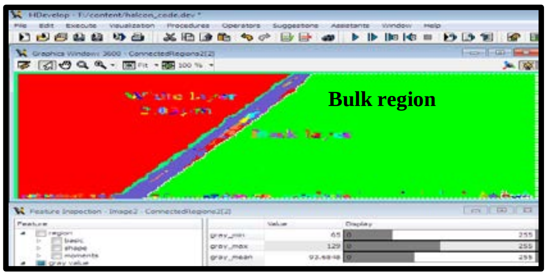
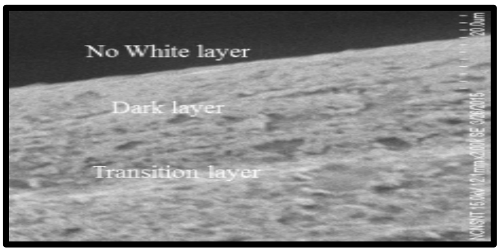
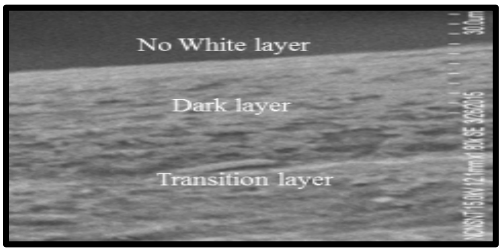


Fig. 6b. Pseudo colour image with auto-threshold values of bulk region for the surface machined without protective gas mixture at the cutting speed 187m/min

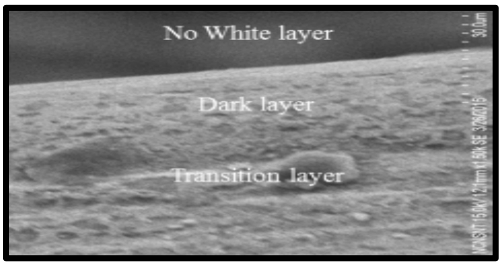
The significant surface morphology is observed from the SEM images illustrated in the Figure 7a, 7b and 7c. All these figures firmly expose the WL free surfaces by the passage of protective gas mixture for the same cutting speeds with its better vapour density, higher vaporization and greater inertness, thus the TMAZ was protected from the thermal impact, shear stress and environmental reactions. Eventually there was a drop in the thermal gradient at the TMAZ. The WL free surfaces were obtained by the protective gas mixture with the temperature decline below austenitic range, uniform heating and quenching. So there were no austenitic decompositions. Also the cutting edge integrity was preserved through smooth chip ejection along the rake face with its speedy discharge [Ke et al. 2009, Cristino et al. 2010]. Since the chips removed were not adhered and gathered at the cutting edge, the abrasion and plowing were absolutely minimized. So less shear stress was initiated; subsequently an insignificant plastic strain was obtained. Hence a significant WL free machined surface was attained for all the cutting speeds. This is appreciably noticed with minor grain pullout due to negligible plastic deformation. Also the transitional zones were observed after the dark layer for all the cutting speeds.



a. (v=125m/min)



b. (v=187m/min)



c. (v=250m/min)

Fig. 7. Surfaces machined with the protective gas mixture

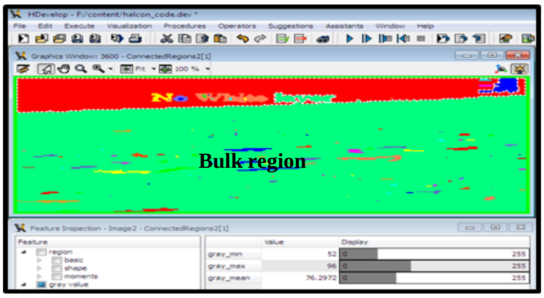


Fig. 8a. Pseudo colour image with auto-threshold values of bulk region for the surface machined with protective gas mixture at the cutting speed 187m/min

To support, the Pseudo color images with auto-threshold gray values are illustrated in the Figure 8a and 8b. It exactly shows only two regions namely bulk and environment in two different pseudo color's green and red, and there are no traces of WL region as found in the earlier images. The auto-threshold gray_mean values of bulk region are greater than the environment region by 1.85 times. It is quite evident, that the WL formation could be evaded by reducing the thermal impact, regulating the heating and cooling, and restricting the environmental reactions with the assistance of protective gas mixture atmosphere.

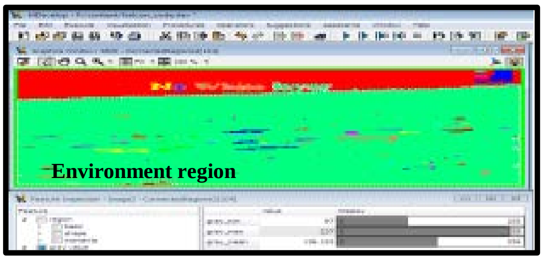


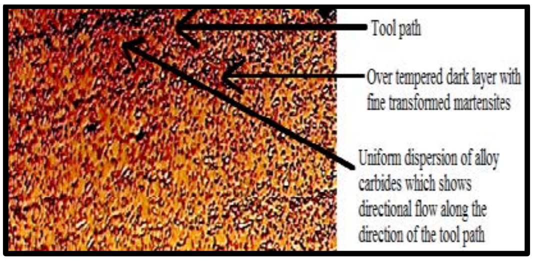
Fig. 8b. Pseudo colour image with auto-threshold values of environment region for the surface machined with protective gas mixture at the cutting speed 187m/min

Microstructure

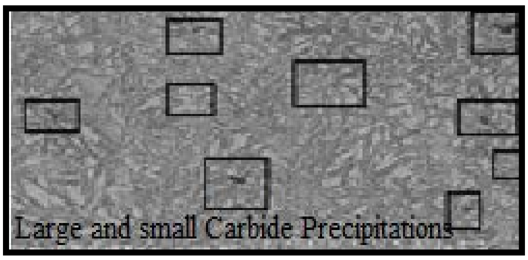
Typically the HT causes adverse changes in the microstructure of the surface, subsurface as well as the mechanical properties of the machined part [Dogra et al. 2011]. Hence these areas are needed to be focused for the improved surface reliability; otherwise the changes in the microstructure shall lead to the WL formation. The WL formation occurs when the TMAZ temperature reaches up to the austenitic range, subsequently quenched by the air. The accumulation of retained austenite is usually depends upon the process conditions and the material being processed [Schwach and Guo 2005]. In addition to the different insert materials, cutting edges, coatings, cryogenic treating of inserts and machining under various cooling; the work materials with coarse grain microstructures will also be helpful in avoiding the WL formation with more depth.

Obviously at the elevated temperatures the coarse grain microstructures are tends to develop less quasi-viscous regions at the machined surface, since it has less number of grain boundaries. As a result there will be an insignificant thermal distortion occurs at the machined surface, therefore the workpiece materials with coarse grained microstructures are preferable for HT [Poulachon et al. 2008]. But that can be achieved only by the additional heat treatments. The microstructural changes in the specimens due to DPT are examined to a critical depth of 100µm [Aramcharoen and Mativenga 2008] with the help of optical microscope images (300X) taken after polishing, etching for about 10 seconds with 2% Nital, later washed and dried with hot air [Dogra et al. 2011].

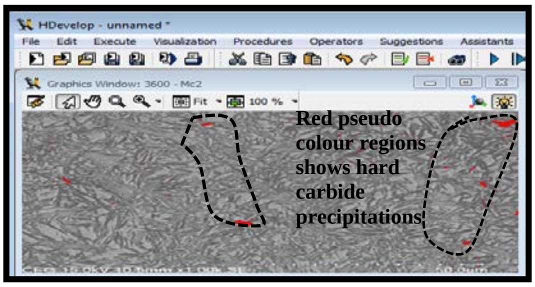
For instance the Figure 9a shows the microstructural changes obtained in the dark layer without the passage of protective gas / DM at the cutting speed 125m/min. It shows the over tempered dark layer with fine transformed martensites, besides evenly dispersed alloy carbides. They are found firmly across the machined surface due to the atmospheric reaction and results in carburization, which shows directional flow along the direction of the tool path. The fragmentation of large and small alloy carbide precipitations dispersed evenly in the fine transformed martensite matrix. The DPT has occurred due to the higher heat intensity, subsequent rapid heating and cooling that result in austenisation. Almost the same microstructures were observed in the other images obtained for other cutting speeds, but the magnitude of the carbides varies substantially with respect to the heat intensity.



a. Microstructure in the dark layer



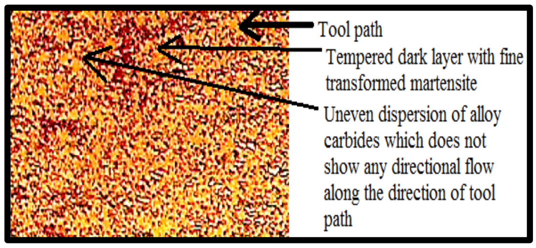
b. Hard carbide precipitations in the dark layer



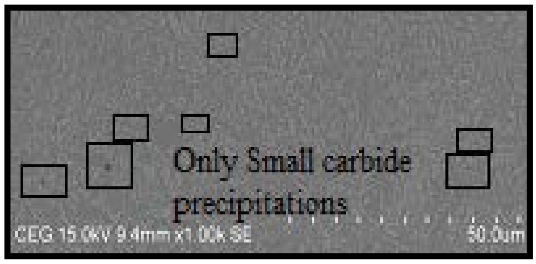
c. Red pseudo colour regions shows the hard carbides

Fig. 9. Surface machined without protective gas mixture at the cutting speed 125m/min

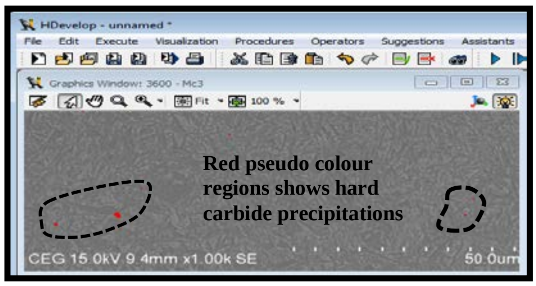
For instance the Figure 9b demonstrates the presence of evenly dispersed large and small hard carbide precipitations in the dark layer. In addition to that the Figure 9c substantiates the presence of hard carbide precipitations in red pseudo colour for the same SEM image by using image processing software *HDevelop*. Within the carbide precipitations, two hard carbides were selected randomly and measured by bounding box method. The large one was measured as 7.5µm length, 3.1µm width; whereas a small one was measured as 2.3µm length and 1.6µm width respectively.



a. Microstructure in the dark layer



b. Hard carbide precipitations in the dark layer



c. Red pseudo colour regions shows the hard carbides

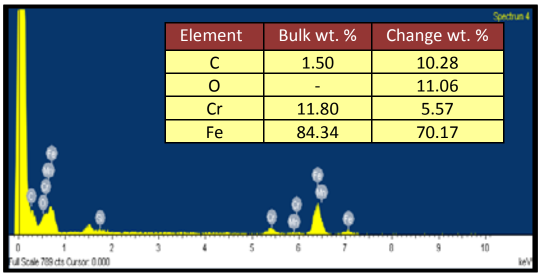
Fig. 10. Surface machined with protective gas mixture at the cutting speed 125m/min

In contrast the Figure 10a reveals a different microstructural changes in the dark layer with the passage of protective gas mixture for the similar cutting speed. It shows only a tempered dark layer with fine transformed martensites. And it is noticed that the DPT has not taken place due to higher heat intensity, subsequent rapid heating and cooling, which did not reach up to the austenitic range. The uniform cooling and heat quenching characteristics of the protective gas mixture has prevented the austenisation. Also observed unevenly dispersed small and very small hard carbide precipitations due to lower surface reactions. But they are not found firmly across the surface; which does not show the directional flow along the tool path direction.

Virtually the same microstructures were observed in the other images obtained for other cutting speeds, but the magnitude of the carbides varies negligibly. The Figure 10b illustrates the presence of unevenly dispersed small and very small carbide precipitations in the dark layer. Moreover the Figure 10c validates the presence of small and very small carbide precipitations in red pseudo colour for the same SEM image by using *HDevelop* software. The small carbides were selected randomly and measured by bounding box method. The small one was measured as 1.7µm length, 1.2µm width, but very small one was dispersed at the submicron level.

Chemical Compositional changes

Usually the key chemical elements are tends to changes their compositions due to the surface or environmental reactions. It has been studied that it is one of the three vital mechanisms of the WL formation apart from the SPD and DPT. And it is observed that there is a sharp increase in carbon and oxygen contents, while there is a diminution of iron and chromium contents, at the machined surface [Bosheh and Mativenga 2006]. Therefore the original weight percentages of the key elements as presented in the bulk are exactly compared with the weight percentages changed due to the surface reactions after the HT. The changes are analyzed using EDAX.



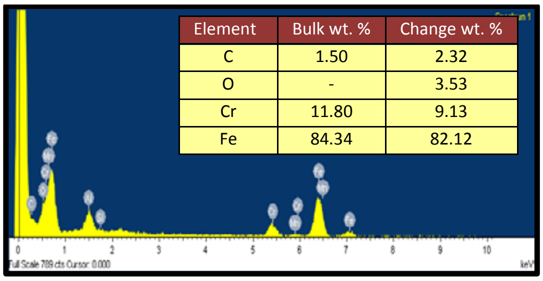
Element	Bulk wt. %	Change wt. %
C	1.50	10.28
O	-	11.06
Cr	11.80	5.57
Fe	84.34	70.17

Fig. 11. Spectrum of the key elements for without protective gas mixture machining at the cutting speed 250m/min

For example the Figure 11 depicts the changes in compositions of the key elements at the machined surface without the passage of protective gas mixture machining/DM at the cutting speed 250m/min. From the evaluation it was found that the carbon content has increased sharply to a larger extent in comparison with the bulk. The reason for this increase was because of carbon diffusion into the surface machined due to carburization. And it was promoted by the higher cutting temperature along with the surface reaction. Similarly a sound oxidation occurred due to the oxygen concentration, which has also made the higher weight percentage as carbon made. Also the diminution of chromium and iron was noticed in comparison with the bulk, because of the higher oxygen enrichment. Though the depth of WL varies due to change in the cutting speeds, the compositional changes closely resemble to each other. Although, there were significant disparities have noticed in the compositions of key elements, there were no sizable changes have occurred in the other elements.

From the other spectrums, it was noted that the oxygen concentration remarkably reduced when the cutting speed decreased. In addition to that it was found that the carbon diffusion was reduced along with the oxygen enrichment, even though more prospects for chemical reactions, due to more contact time between the atmosphere and surface machined. Therefore the oxygen enrichment and subsequent carbon diffusion was reduced due to comparatively lower heat intensity. This deduces that the surface reactions were not only influenced by time, whereas it was also influenced by the higher cutting temperature, induces more chemical reactions. Nearly same changes were observed for other cutting speeds.

The Figure 12 neatly depicts a different mode of change in the compositions of the key elements at the surface machined under the protective gas mixture machining for the same cutting speed. With the help of 26% more vapor density against air, the protective gas effectively shielded [Cristino et al. 2010] the TMAZ and made a prominent reduction in both carburization and oxidation. It was studied that the carbon content was almost close to the bulk. However, oxidation occurred at the machined surface even though there was a protective gas mixture effect. Though there was an ample change in the iron diminution, chromium had only notable increase in its weight percentage. Moreover the iron and chromium weight percentage increased gradually towards the bulk as shown in the spectrum. It was noted that the reduction in temperature effectively reduced the surface reactions in addition to the protective gas mixture atmosphere. Practically same changes were observed for other cutting speeds.



Element	Bulk wt. %	Change wt. %
C	1.50	2.32
O	-	3.53
Cr	11.80	9.13
Fe	84.34	82.12

Fig. 12. Spectrum of the key elements for protective gas mixture machining at the cutting speed 250m/min

CONCLUSION

The Argon-CO_2 protective gas mixture has curbed the vital mechanisms responsible for the WL formation mainly by reducing the cutting temperature due to vaporization, regulating cooling through convection and restricting environmental reactions. During HT the protective gas mixture atmosphere, significantly bestowed the following than without protective gas mixture machining for enhancing the surface reliability by eliminating WL.

1. An average temperature reduction at the machined surfaces were witnessed between 221.9°C to 236.3°C, whereas the chips removed were observed from 296.0°C to 386.9°C due to effective vaporization, which largely encouraged a significant heat sink at the TMAZ.
2. The inertness of this gas mixture has greatly ensured safe operations, even though there were more sparking. Also the speedy propulsion of gas mixture not only prevented the chips from burning but also drove away the blazed chips gathered at the cutting edge thus averted the adhesion and built-up-edge formation.
3. A fine chip removal was encouraged with negligible abrasion and plowing effect, so the mean surface roughness was obtained around 0.22µm, by which traditional grinding can be replaced.
4. Certainly there were no DPT due to higher thermo-mechanical stress intensities and cooling disparities, which encouraged only dark layer with fine transformed martensites besides uneven dispersion of small and very small hard carbide precipitations. Virtually most of the small carbides were noticed and measured in micron level. But very small carbides precipitations could not be measured, since they have dispersed at the submicron level.
5. Absolutely the chemical reactions between the atmosphere and surfaces machined were sensibly restricted; hence there were marginal increase in the carburization and oxidation also marginal diminution in the iron and chromium elements. In addition to the protective effect of the gas mixture, reduction in cutting temperature also helped in reducing the chemical reactions.
6. Finally the WL formation was eliminated under the Argon-CO_2 protective gas mixture atmosphere with compatibility over environment, workpiece material, cutting insert, machine tool and personnel involved. Hence it can be considered as green manufacturing.

ACKNOWLEDGEMENT

The authors hereby thank the Rajalakshmi Engineering College, Thandalam, Chennai and DoME, CEG, Anna University, Chennai for their encouragements, constant supports also providing the facilities for carrying out this study successfully.

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NOMENCLATURE

AISI D2 high carbon high chromium tool steel

Al_2O_3 aluminium oxide

HRC Rockwell hardness C- scale

l/d aspect ratio

µm micrometer

m/min meter per minute

mm/rev millimeter per revolution