WHITE LAYER SUPPRESSION AND SURFACE INTEGRITY ENHANCEMENT IN HARD TURNING OF AISI D3 STEEL USING CBN INSERTS UNDER DRY AND GAS MIXTURE COOLING

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ABSTRACT

Superalloys and hardened steels are widely used across industries due to their superior mechanical properties, including high hardness, toughness, wear resistance, and fatigue strength. Because of these characteristics, they typically require grinding for final finishing; however, grinding operations demand expensive machinery, specialized equipment, high-cost abrasive wheels, lengthy setup procedures, and extended machining cycles. As a result, hard turning has emerged as a preferred alternative for finishing hard-to-cut materials, offering advantages such as reduced lead time, lower setup and tooling costs (no fixtures or form wheels), and decreased energy and coolant requirements. In addition, hard turning (HT) can achieve better part quality compared to conventional grinding. However, the process is often affected by the formation of a detrimental surface feature known as the white layer (WL), which significantly reduces fatigue life and undermines surface reliability due to dynamic phase transformations. In this study, super-hardened AISI D3 steel was machined using a semi-worn CBN insert under dry machining and gas-mixture cooling conditions. The results indicate that dry machining neither eliminated the WL nor improved surface finish, whereas gas-mixture cooling effectively suppressed WL formation and produced superior surface quality.

KEYWORDS: CBN, dry machining, gas mixture cooling, hard turning white layer

1. INTRODUCTION

Principally, steels with hardness values above 45 HRC are finished through hard turning (HT) [1]. This process can be performed using tungsten carbide, cermet, or CBN inserts, with or without tool coatings [2], and requires advanced, high-precision machine tools. Although HT offers several advantages, it often results in the formation of a surface defect known as the white layer (WL). This layer is unstable and tends to degrade under cyclic loading, thereby significantly reducing the fatigue life of the component. The formation of WL is generally attributed to severe plastic deformation, rapid heating followed by quenching, and thermochemical reactions at the cutting interface [3]. Cutting speed plays a crucial role, and WL formation at lower surface speeds is typically associated with Mechanically Driven Phase Transformation (MDPT). At moderate cutting speeds, WL formation is primarily attributed to Thermo-Mechanically Driven Phase Transformation (TMDPT), whereas at higher cutting speeds, it occurs predominantly due to Thermally Driven Phase Transformation (TDPT). In general, WL is characterized by a high proportion of retained austenite [4]. Although coolants are known to reduce the thickness of WL, they tend to vaporize rapidly at the tool–workpiece interface, forming a hot vapor film within the Thermo-Mechanically Affected Zone (TMAZ) [5], which limits their effectiveness in controlling thermal gradients. As a result, the inserts undergo rapid wear due to high thermo-mechanical stresses. The absence of coolants further accelerates tool wear under these stresses [6]. It has been reported that HT machining performed under dry machining (DM) and near-DM conditions leads to significantly higher tool wear [7]. In contrast, cryogenic cooling effectively reduces cutting temperature and promotes lower shear deformation compared to flood cooling and DM [8]. It is also well established that a WL can

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form under all cooling conditions. Previous studies confirmed that gas-based cooling offers better reduction in temperature, cutting forces, and surface roughness [9-10]. Therefore, an attempt was made to achieve sustainable manufacturing through Gas–Minimum Cooling (GMC), with the objective of eliminating WL formation and improving surface finish, while ensuring compatibility with the workpiece material, cutting tool, machine tool, operator safety, and environmental considerations.

2. MATERIALS, CUTTING INSERT AND METHOD

In this study, High Carbon and High Chromium cold-working tool steel (AISI D3) was selected due to its high hardness, superior heat and wear resistance, and adequate toughness. The chemical composition of the material is presented in table 1. CBN inserts were chosen for the hard turning operation because they offer excellent heat and wear resistance, along with outstanding physical and chemical stability. Moreover, CBN tools are particularly suitable for machining ferrous alloys [11]. Hence, CBN was selected as the cutting tool material for this investigation.

An Argon (80%)-Helium (20%) gas mixture with 99% purity was selected to provide effective cooling as well as a protective atmosphere during hard turning. This mixture [12] exhibits strong quenching capability, higher density, lower thermal conductivity, and complete inertness, along with being non-toxic and non-flammable. Its physical and chemical properties are presented in Table 2. The gas mixture was supplied through a single nozzle at a pressure of 0.7 MPa [13]. The compatibility of the selected gas mixture was verified in accordance with ISO 11114-1 (Part 1, July 1998) and ISO 11114-2 (Part 2, March 2001).

The surface speeds (Vc) were selected in the range of 30–200 m/min, while the feed rate (f) varied between 0.06–0.18 mm/rev. The depth of cut (a) was kept constant at 0.1 mm. Cylindrical workpieces of 150 mm length and 30 mm diameter (l/d < 10 as per ISO 3685) were pre-machined and air-hardened to a hardness of 61–62 HRC. Hard turning experiments were conducted on a GEDEE WEILER MLZ 250V lathe using an uncoated, semi–worn-out CBN insert (TNMA160408, CB7015 grade) with a honed edge, mounted on an MTJNL2525M16 tool holder. A nose radius of 0.8 mm and an initial flank wear of 0.2 mm were selected in accordance with ISO 3685 [14].

Recent studies have reported significant improvements in eliminating white layer formation and enhancing surface finish under similar conditions [15–19]. The results obtained in the present study pertaining to cutting forces, surface roughness (Ra), and WL formation under DM and GMC during hard turning are discussed in the following section.

Table 1. Chemical composition of AISI D3 steel

Chemical composition	C	Cr	Mo	V	Mn	Si	Cu	Others	Fe
% (by wt.)	2.1-2.4	11-13	0.7-1.2	1	0.6	0.6	0.25	0.06	Bal.

Table 2. Physical and chemical properties of the Ar (80%)-He (20%) gas mixture

Sample	Description	Properties
1	Color	Colorless
2	Odor	Odorless
4	Vapor density (gm./cc)(Air = 1)	1.24
5	Boiling/condensation point(°C)	-185.9
6	Melting/freezing point (°C)	-189.4
7	Critical temperature (°C)	-122.3
8	Thermal conductivity (W/m/° K) (Air = 0.0257)	0.041

3. RESULTS AND DISCUSSION

In machining, force components are critical to understanding cutting mechanisms and tool behavior. In conventional soft turning, the radial force is typically only 0.3–0.5 times the tangential force. However, in hard turning, the radial force often dominates. This is especially true when the depth of cut is small relative to the insert’s nose radius. In our study, we used a depth of cut of 0.1 mm and a nose radius of 0.8 mm, which contributes to a significantly larger radial force compared to the tangential force. Additionally, radial forces become more prominent when the depth of cut is below 0.3 mm. These forces are highly sensitive to tool condition and increase significantly once the flank wear exceeds the critical value of 0.025 mm. An increase in feed rate also leads to higher mean radial forces due to the larger cross-section of the sheared chip. Thermal softening of the workpiece further contributes to reduced cutting forces, as the heat generated in the shear zone softens the material ahead of the cutting edge, thereby lowering the required cutting energy.

At higher cutting speeds (above 140 m/min), thermal stresses become substantial, leading to adhesion, built-up edge (BUE) formation, and intermittent residual cutting action. Conversely, at medium and lower cutting speeds, plastic deformation and severe plastic deformation (SPD) are more likely to occur. Therefore, the radial force component plays a crucial role in evaluating the thermo-mechanical effects acting on the machined surface.

In fact, excessive heat generation and uneven cooling promote thermal softening of the workpiece material, which in turn affects machinability through plastic instability. Higher mean radial forces are also observed due to chip accumulation, adhesion, built-up edge (BUE) formation, and the resulting intermittent residual cutting action.

From the plots shown in Figure 1, it is evident that the mean radial forces decrease at cutting speeds of 110 m/min and 200 m/min, mainly due to thermal softening under dry hard turning conditions. However, at the lower cutting speed of 30 m/min, severe plastic deformation (SPD) contributes to an increase in mean radial forces. It is also observed that an increase in feed rate leads to higher mean radial forces at any given speed, owing to the larger cross-sectional area of the sheared chip.

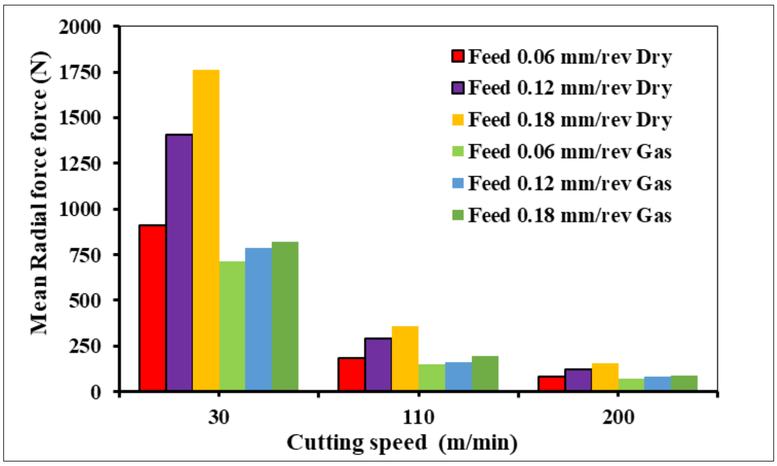

Fig. 1. Mean radial force obtained in the dry and gas mixture cooling

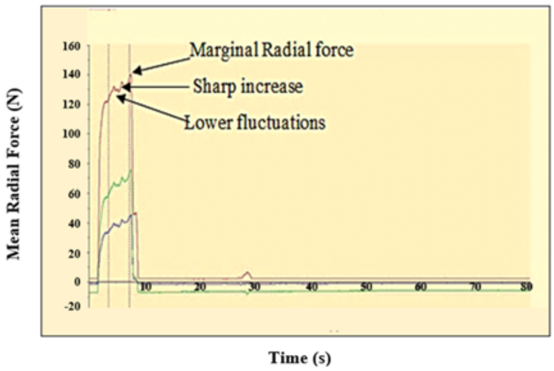

Fig. 2. Force components in Dry machining: Mean radial force=154.7N, v=200m/min, f =0.18mm/rev

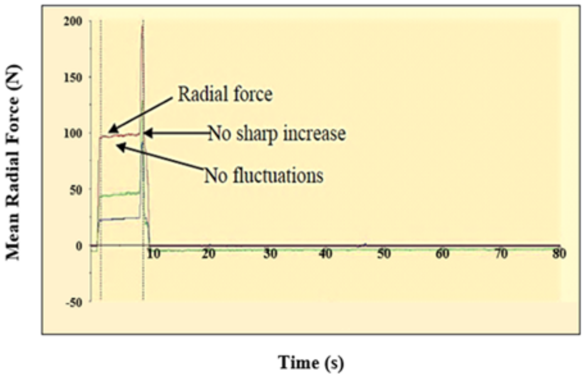

Fig. 3. Force components under gas mixture cooling: Mean radial force=90.3N, v=200m/min, f =0.18mm/rev

It is observed that the mean radial forces decrease substantially with increasing cutting speed under gas-mixture–cooled HT, owing to improved machinability and enhanced plastic stability. Notably, at cutting speeds of 110 m/min and 200 m/min, the mean radial forces reduce appreciably due to shear-stress-free machining conditions. In contrast, lower cutting speeds produce relatively higher radial forces because of increased shear stress at the tool–work interface. Overall, machining under gas cooling and the GMC condition yields significantly lower and more stable radial forces. The rapid evacuation of chips under these conditions minimizes chip accumulation, adhesion, and BUE formation, thereby eliminating any residual cutting action from adhered chips. As a result, gas cooling demonstrates superior heat dissipation, leading to reduced radial force generation. Furthermore, figure 2 shows higher radial forces with sharp increases and fluctuations under DM, whereas figure 3 clearly illustrates lower forces with no sudden rise or fluctuation under GMC at v = 200 m/min, f = 0.19 mm/rev, and a = 0.1 mm.

Surface roughness is typically the first indicator of surface integrity assessed after machining a component, making its characterization one of the most critical quality measures of a machined surface. As expected, an increase in feed rate deteriorates the surface finish; therefore, the feed range of 0.08–0.20 mm/rev significantly influences surface roughness. In general, cutting speed improves surface finish, particularly within the stable machining range of 120–180 m/min. From figure 4, it is evident that the lower cutting speed of 30 m/min results in higher surface roughness due to severe plastic deformation and system instability. At the medium cutting speed of 110 m/min, reduced roughness is observed owing to improved system stability and lower radial forces. However, at the high cutting speed of 200 m/min, surface roughness increases again, mainly due to intensified abrasive interactions. Additionally, for any given cutting speed, an increase in feed rate further elevates surface roughness because of intensified rubbing between the tool and workpiece.

Figures 5a and 5b illustrate the surface roughness obtained under DM and GMC at V = 200 m/min, f = 0.06 mm/rev, and a = 0.1 mm. Under DM, the mean surface roughness increases progressively as the feed rate rises from 0.06 mm/rev to 0.20 mm/rev, primarily due to intensive rubbing between the tool and workpiece. Additionally, the higher cutting forces in DM promote system instability at the lower cutting speed of 30 m/min, while intensive shearing at the high cutting speed of 200 m/min further contributes to instability. Accumulation and adhesion of chips, followed by BUE formation and subsequent abrasive interaction between adhered chips and the machined surface, further deteriorate the surface finish. As discussed earlier, the moderate cutting speed yields the lowest surface roughness because of reduced rubbing and improved system stability.

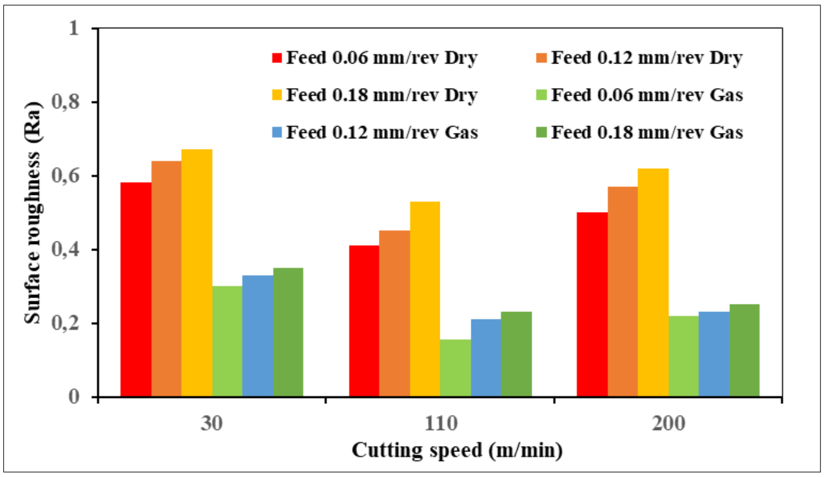

Fig. 4. Surface roughness obtained under dry and gas mixture cooling

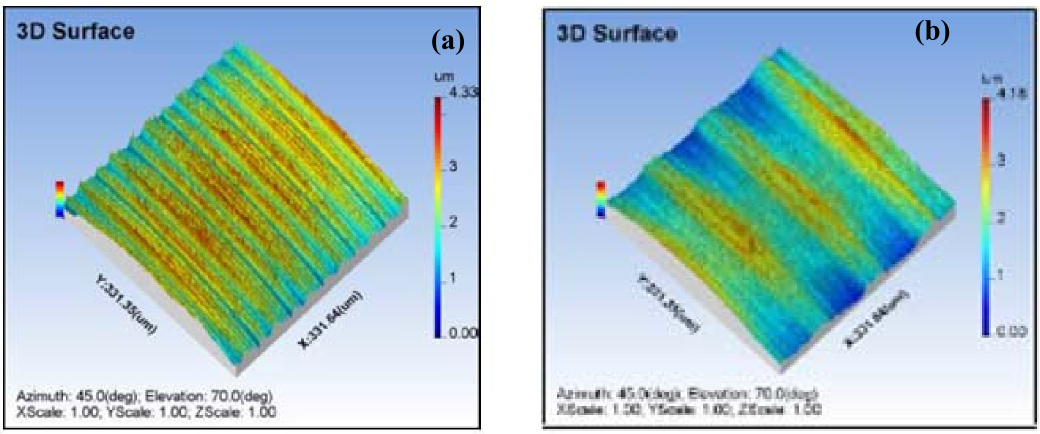

Fig. 5. Obtained surface roughness: a) 3D Image of roughness in dry machining (*Ra* = 0.501µm obtained, *V*= 200 m/min *f* = 0.06 mm/rev, *a* = 0.1 mm); b) 3D Image of roughness in gas mixture cooling (*Ra* = 0.226µm obtained, *V*= 200 m/min *f* = 0.06 mm/rev, *a* = 0.1 mm)

It is observed that the high-velocity propulsion of the GMC stream enhances machinability by promoting improved shearing and effective chip control. At the high cutting speed of 200 m/min, smooth machining is achieved due to the complete elimination of chip accumulation, adhesion, BUE formation, and the subsequent abrasive effects of detached chips. However, system instability remains inherent at the low cutting speed of 30 m/min because of elevated cutting forces, whereas absolute system stability is attained at the medium cutting speed of 110 m/min. The surface roughness values produced under both DM and GMC are sufficiently low to serve as a potential alternative to conventional grinding, where the typical minimum roughness is around 1.6 µm.

The combined thermal, mechanical, and chemical interactions during hard turning promote WL formation. These interactions cause mechanical and metallurgical alterations at the machined surface through different phase-transformation mechanisms. Generally, lower cutting speeds encourage MDPT, medium cutting speeds facilitate TMDPT, and higher cutting speeds induce TDPT. Collectively, these transformations lead to the development of a disturbed surface pattern known as the white layer, supported by surface reactions. Thus, WL formation and its thickness are strongly influenced by localized and coupled thermal-mechanical-chemical effects.

From the plot shown in figure 6, it is evident that the mean WL thickness increases with rising cutting speed. This trend is attributed to the corresponding increase in cutting temperature caused by intensified shearing and elevated thermal loads at higher speeds. Similarly, for a given cutting speed, an increase in feed rate results in a thicker WL. This is primarily due to higher friction at the tool–work interface, as well as chip adhesion, BUE formation, and the subsequent abrasive action of removed chips, all of which intensify the thermo-mechanical effects that promote WL growth.

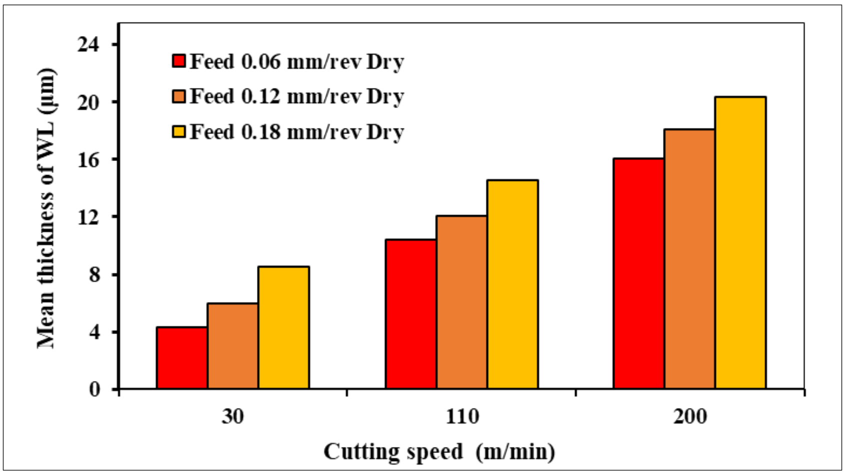

Fig. 6. Mean thickness of WL in DM

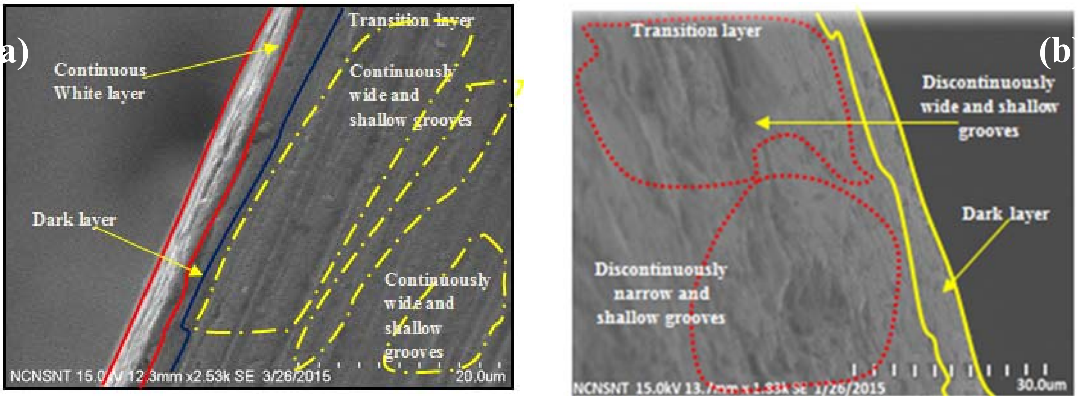

Fig. 7. a) SEM Image of DM (at V = 200m/min, f = 0.18 mm/rev, a = 0.1 mm), b) SEM image of GMC, V = 200m/min, f = 0.18 mm/rev, a = 0.1 mm

During DM, the mean WL thickness ranges from approximately 4.32 µm to 8.32 µm at the low cutting speed of 30 m/min, primarily due to MDPT. At the medium cutting speed of 110 m/min, WL thickness increases to about 10.41–14.53 µm, corresponding to TMDPT. At the high cutting speed of 200 m/min, WL thickness further rises to about 16.05–20.36 µm, governed by TDPT.

Figure 7a illustrates this clearly, showing a mean WL thickness of 20.36 µm under TDPT at V = 200 m/min, f = 0.18 mm/rev, and a = 0.1 mm. Additionally, extrusion effects are evident due to heightened plastic instability, resulting in multiple localized stretches manifested as continuously wide, deep, and shallow grooves. In contrast, GMC (Fig. 7b) did not generate any WL at any cutting speed. This absence is attributed to its superior heat-extinguishing capability, lower thermal conductivity, improved cooling uniformity, and higher relative density compared to atmospheric air. Only a few discontinuously wide and shallow grooves, along with narrow and shallow grooves, were observed likely due to negligible plastic strain.

4. CONCLUSIONS

This study attempted to improve surface finish and eliminate WL formation using GMC, and the following conclusions were drawn.

a) WL is a harmful laminated surface layer produced by MDPT/TMDPT/TDPT under dry and conventional cooling, leading to delamination and reduced fatigue life.
b) The higher quenching capacity of the Argon (80%)–Helium (20%) GMC lowered the TMAZ temperature without forming a quasi-viscous state, thereby reducing thermal stress and eliminating plastic strain.
c) The lower thermal conductivity (≈76.5% less than air) and higher relative density (≈24% more than air) enabled controlled convection cooling, suppressing rapid heating/cooling and thermal softening. Consequently, GMC reduced cutting forces by about 170.8–201.2% compared to DM, avoiding SPD.
d) Chip evacuation was greatly improved under GMC, preventing rubbing, friction, ploughing, chip adhesion, BUE formation, and abrasive wear. As a result, surface roughness decreased by about 200.7–257.2% relative to DM.
e) GMC effectively suppresses WL-forming mechanisms by lowering temperature through vaporization, regulating cooling by convection, and limiting environmental surface reactions.
f) Overall, WL forms mainly due to MDPT/TMDPT/TDPT during HT, whereas GMC successfully eliminates WL by restraining SPD, rapid thermal cycling, and surface reactions, thereby improving surface finish.

The future directions will be focused on HT performed, under other inert gases and its mixtures. Moreover, multiple nozzles delivery system can be used. Also, even higher machining parameters can be applied.

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