INFLUENCE OF SURFACE ROUGHNESS ON FATIGUE LIFE OF AISI D3 COMPONENT HARD TURNED BY CBN INSERT UNDER DRY MACHINING

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ABSTRACT

Hard turning has been broadly attributed as a surrogated process for customary grinding because it facilitates any intricate profiles with a single setting. It is a precise machining process, that could accomplish remarkable dimensional accuracy, geometrical tolerance and surface finish, and also ensures coolant-free machining for super hardened steels and alloys. Still, the parts produced are affected by the adverse surface integrity along with a surface pattern often called a White Layer. As a result, the parts produced are affected by fatigue life due to cyclic loads. This investigation attempted to analyse surface roughness against the Fatigue life of AISI D3 component hard turned by semi-worn out CBN insert under the dry machining. L27 orthogonal array was designed with three cutting speeds, feed rates and depth of cuts. ANNOVA table was formed and found that the feed rate influenced around 62.4% on the surface roughness, subsequently depth of cut impacts nearly 26.6% and cutting speed implies 11%. In addition, it was revealed that the surface roughness influences the Fatigue life of the part. The lowest surface roughness has produced highest Fatigue life of 2.8×107 cycles.

KEYWORDS: fatigue, hard turning, CBN insert, AISI D3, dry machining

1. INTRODUCTION

Super-hardened steels with hardness values above 45 HRC [1] can be effectively finish-turned as an alternative to conventional grinding operations. This process is efficiently carried out using Cubic Boron Nitride (CBN) inserts [2], with or without coatings such as TiN or TiCN. This high-precision machining process, applicable to super-hardened steels and superalloys, enables the achievement of exceptionally high dimensional accuracy and tight geometrical and surface tolerances often less than a micron [3]. The process is commonly referred to as hard finish turning, or more widely known as Hard Turning (HT). The HT is found to be successful only with the hi-tech advancements provided in the contemporary machine tools by incorporating sturdiness and stunning tool sliding movements, for the huge throughput, without compromising the quality [4]. As studied earlier, the microstructure, microhardness, surface finish, chemical compositional changes, residual stresses and White Layer formation are considered to be the important factors for surface reliability [5]. Even though numerous advantages have been attributed to Hard Turning (HT) [6], certain limitations have been identified concerning the surface integrity or surface finish quality of the machined components [7]. As mentioned earlier, surface reliability generally encompasses factors such as surface morphology, microstructure, microhardness, compositional variations, and residual stresses. In practical applications, Hard Turning (HT) often results in poor surface patterns [8] due to phase transformations that lead to the formation of a surface layer commonly known as the white layer (WL) [9]. This layer has been named after its nature of existence under microscopic examinations.

The WL formed on hard-turned surfaces is typically about 30% harder than the bulk material and is often associated with the presence of tensile residual stresses. In contrast, the underlying dark layer is approximately 60% softer than the bulk material. The dark layer generally appears between the white layer and the transitional layer. Over time, it tends to

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delaminate under high cyclic stresses; consequently, the WL is considered highly detrimental to the fatigue life of the machined components [10]. Therefore, such layers must be removed from the HT surface [11-12], as they significantly reduce the service life of the manufactured parts.

In this research, an attempt has been made to investigate the relationship between surface roughness and the fatigue life of the hard-turned components. The foremost aspect of surface reliability is surface roughness, as it plays a crucial role in determining the functional life of a component. In general, lower surface roughness enhances lubrication between mating surfaces and thereby improves service life. However, excessive cutting temperatures during machining can lead to the formation of heat mounds, which serve as sites for crack initiation. These cracks subsequently propagate, resulting in premature failure. Therefore, minimizing surface roughness is essential to prevent crack initiation and propagation.

To achieve this, the design of experiments approach was employed to determine the optimal combination of machining parameters. In this investigation, an orthogonal array was adopted to achieve the desired reduction in surface roughness, and analysis of variance (ANOVA) was performed to validate the results statistically. Consequently, an improvement in the fatigue life of the hard-turned components was observed.

2. MATERIALS AND METHODS

The workpiece used in this study is AISI D3, a high-carbon, high-chromium tool steel corresponding to W-Nr. 1.2379. Its chemical composition is 2.1% C, 13.5% Cr, 1.2% Mo, 1.0% V, 0.6% Mn, 0.6% Si, with the balance being Fe. This steel grade exhibits high indentation hardness, excellent wear and heat resistance, and relatively low ductility. In the annealed condition, it possesses a hardness of approximately 45 HRC and can be air-hardened to 61-62 HRC. Due to its high abrasion resistance in the hardened state, finishing operations are typically restricted to conventional grinding. Therefore, hard turning was selected as the finishing process for this material in the present investigation.

The cutting tool employed in this investigation was a CBN insert containing 80% cubic boron nitride and 20% TiN ceramic phase. SNGA120412T01020A inserts with a chamfered-edge micro-geometry of 0.1 mm × 20° were used, along with a DSBNR2525M12 tool holder. CBN is preferred for machining super-hardened steels due to its exceptional hot hardness, superior wear resistance, and high chemical and thermal stability. Unlike polycrystalline diamond (PCD), CBN is well suited for hard turning of ferrous alloys. CBN inserts have been widely recognized as a technologically viable tool material for producing components with the required dimensional and surface integrity. hard turning using CBN inserts serves as an effective alternative to conventional grinding operations. The physical properties of the CBN inserts used in this study are presented in table 1.

Table 1. Physical properties of CBN

Properties	**Values**
Hardness	2800 HV
Tenacity	4.2 MPa
Young’s Modulus	570 Gpa
Density	4.3 g/cm^3
Specific heat	750 J/Kg/°C
Thermal Conductivity	100 W/m/°K
Thermal expansion	4.9x10^-6 mm/°C

The experiments were performed on a CNC JOBBER XL turning centre (Fig. 1a) equipped with a 15-kW spindle and capable of operating at speeds up to 4000 rpm. The workpieces were initially rough-turned under dry machining conditions. Subsequently, they were heat-treated by oil quenching and then tempered at 60 °C for 15 minutes prior to the hard turning trials. To reduce brittleness and residual stresses, and to enhance ductility and toughness, the workpieces were tempered at 173 °C for 1.5 hours. After tempering, they were allowed to cool naturally to room temperature. The hardness of each specimen was measured and confirmed to be in the range of 63–65 HRC.

The cutting parameters selected (factor and levels) for machining the ASTM-standard fatigue test specimens were as shown in table 2. This set of machining parameters was recommended by the tool manufacturer (Sandvik) for ceramic-reinforced CBN inserts and has also been adopted in earlier studies. The surface roughness of the machined samples was measured using a 2D surface roughness tester (Taylor Hobson). Fatigue testing was conducted using an original railroad-axle-type Rotating Bending Testing Machine, in which the bending moment remains constant along the entire specimen length. The fatigue test setup used to determine fatigue life is shown in figure 1b, and the prepared fatigue test specimen is presented in figure 1c. The testing machine has a maximum loading capacity of 200 kg/cm². Based on the selected combinations of machining parameters, an L27 orthogonal array was formulated for conducting the experiments.

3. RESULTS AND DISCUSSION

Surface roughness is a key indicator of the surface integrity of machined components and plays a crucial role in evaluating cutting tool performance. In this study, Analysis of Variance (ANOVA) was employed to determine the influence of machining parameters on surface roughness. Based on the selected factor levels (Table 2), an L27 orthogonal array was formulated, as presented in table 3. Since each machining parameter was assigned three levels, the L27 array was appropriate for the experimental design. The ANOVA results generated using Design Expert 7 for the various cutting conditions are summarized in table 4. Surface roughness was the output response. Surface roughness affects not only the dimensional accuracy of the machined parts but also their functional properties, making its analysis essential for assessing machining performance.

In the HT process, surface roughness is significantly influenced by several factors, including tool nose radius, workpiece hardness, tool geometry, and cutting parameters. The ANOVA results indicate that feed rate is the most dominant factor, contributing approximately 62.40% to the variation in surface roughness. Cutting speed has a moderate influence of about 26.6%, while depth of cut contributes the least, at around 11%.

The results show that lower surface roughness values are obtained at higher cutting speeds due to reduced cutting forces and improved plastic instability at the tool–workpiece interface. At higher feed rates, however, thermal softening increases the extent of plastic deformation, leading to greater surface irregularities. Additionally, the formation and accumulation of adhered material, built-up edge (BUE), and chip abrasion further contribute to increased roughness. At lower cutting speeds, the surface roughness tends to be higher due to elevated cutting forces and more severe plastic deformation of the machined surface.

Table 2. Factors and the levels for the experiments

Factors	Level 1	Level 2	Level 3
Cutting speed (Vc), m/min	120	150	180
Feed rate (f), mm/rev	0.06	0.10	0.15
Depth of cut (d), mm	0.05	0.1	0.15

Fig. 1. Equipment and materials: a) high-speed CNC lathe; b) fatigue testing setup; c) fatigue test specimen

Table 3. Experimental design matrix as per orthogonal array L_{27} for 'R_a' response

Test	Cutting speed [m/min]	Feed [mm/rev]	Depth of cut [mm]	Roughness [R_a]
1	120	0.06	0.05	0.63
2	120	0.06	0.10	0.82
3	120	0.06	0.15	0.76
4	120	0.10	0.05	1.08
5	120	0.10	0.10	1.43

Test	Cutting speed [m/min]	Feed [mm/rev]	Depth of cut [mm]	Roughness [R_a]
6	120	0.10	0.15	1.40
7	120	0.15	0.05	1.90
8	120	0.15	0.10	1.93
9	120	0.15	0.15	2.01
10	150	0.06	0.05	0.75
11	150	0.06	0.10	0.64
12	150	0.06	0.15	0.58
13	150	0.10	0.05	1.41
14	150	0.10	0.10	1.34
15	150	0.10	0.15	1.10
16	150	0.15	0.05	1.67
17	150	0.15	0.10	1.58
18	150	0.15	0.15	1.71
19	180	0.06	0.05	0.37
20	180	0.06	0.10	0.51
21	180	0.06	0.15	0.47
22	180	0.10	0.05	0.65
23	180	0.10	0.10	0.67
24	180	0.10	0.15	0.61
25	180	0.15	0.05	1.04
26	180	0.15	0.10	1.19
27	180	0.15	0.15	1.33
			Average	0.83

Table 4. ANOVA results for surface roughness

Factors	SS	D.O. F	MS	F-value	p-value
A-d	0.05	2	0.025	0.120	0.110
B-f	0.20	2	0.35	0.581	0.624
C-V_c	0.22	2	0.11	0.890	0.266
AB	4	0.10	0.84	0.539	-
AC	4	0.059	0.47	0.754	-
BC	4	0.018	0.14	0.961	-
Error	1.00	8	0.12	-	-
Total	2.30	26	-	-	-

The plots shown in figures 2, 3, and 4 illustrate the interaction effects of feed rate, depth of cut, and cutting speed on surface roughness. These results indicate that surface roughness is strongly influenced by cutting speed, primarily due to system instability, chip adhesion, built-up edge (BUE) formation, and residual material removal.

Feed rate also exhibits a major influence on surface quality, as increasing the feed rate increases the cross-sectional area of the sheared chip at a given cutting speed, leading to a rougher surface finish. In contrast, depth of cut shows only a minimal effect on surface roughness compared with feed rate. To further investigate the surface integrity, particularly the formation of the white layer, the machined samples were examined using a Scanning Electron Microscope (SEM).

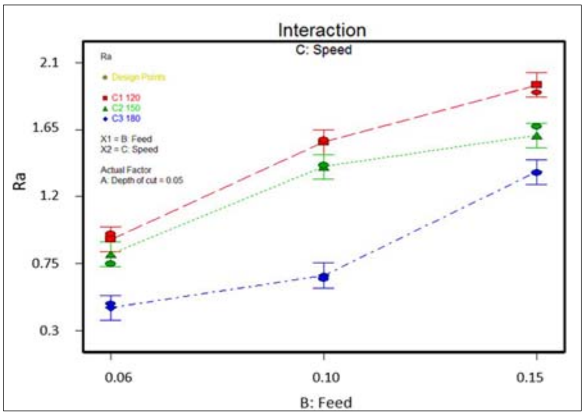

Fig. 2. Interaction between feed, cutting speeds and roughness at depth of 0.05 mm

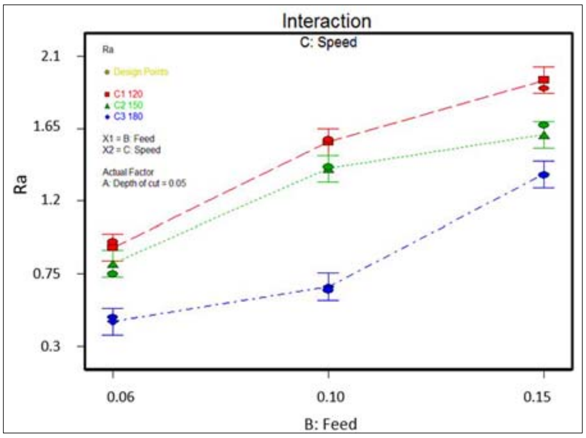

Fig. 3. Interaction between feed, cutting speeds and roughness at depth of 0.10 mm

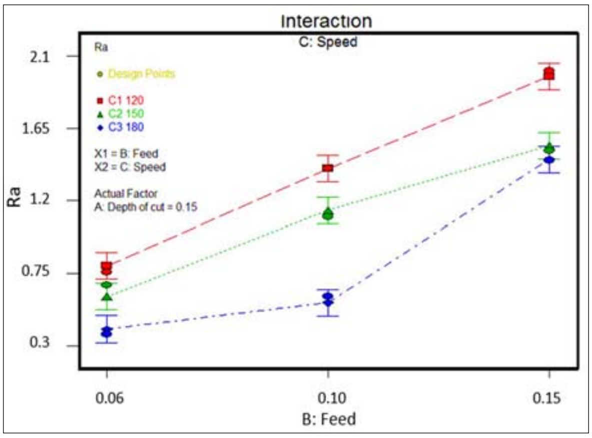

Fig. 4. Interaction between feed, cutting speeds and roughness at depth of 0.15 mm

The primary causes of white layer formation are microstructural alterations induced by high temperatures, severe plastic deformation, and chemical reactions occurring during the machining process. The white layer is a very thin, hardened surface layer that forms on the machined workpiece and is significantly harder than the underlying material. Its formation is typically associated with a phase transformation, often resulting in a layer enriched with retained austenite or other metastable structures. The typical thickness of the white layer is approximately 10 µm. The depth of the white layer can vary depending on the thermal, mechanical, and chemical conditions present within the bulk material. In hard turning, white layer formation can occur under all cutting speed conditions due to mechanically driven, thermo-mechanically driven, and thermally driven phase transformations. For example, at a cutting speed of 120 m/min, feed rate of 0.15 mm/rev, and depth of cut of 0.15 mm, a distinct white layer was observed, as illustrated in figure 5.

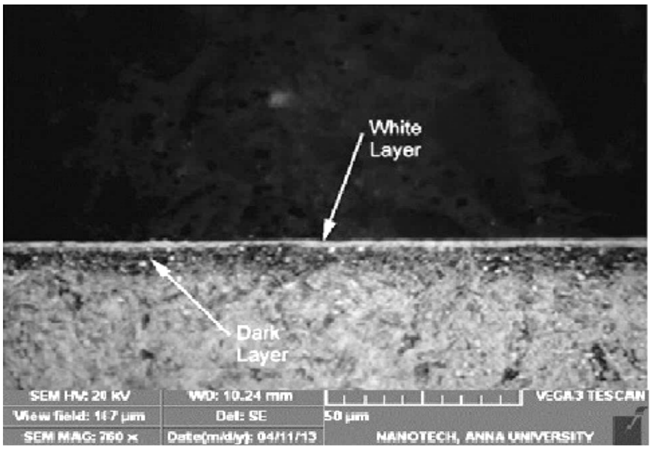

Fig. 5. SEM image of white layer formation

All specimens were tested up to their fatigue limit under a constant bending moment. The fatigue tests were conducted in accordance with ASTM E1049, which is primarily used for determining the number of cycles to failure. Among the tested samples, specimen of test no. 19 with Ra = 0.37 µm endured 2.82.8 × 10^7 cycles, while, specimen of test no. 9 with Ra = 2.01 µm endured 2.1 × 10^7 cycles.

These results clearly demonstrate that fatigue life is strongly influenced by surface integrity, particularly surface roughness. A smoother machined surface corresponds to longer fatigue life, whereas increased roughness promotes earlier crack initiation and reduces fatigue strength.

4. CONCLUSIONS

Several important findings on the hard turning of hardened AISI D3 steel using CBN tools are drawn:

a) feed rate was identified as the most influential parameter on surface roughness, contributing 62.40%, followed by cutting speed and depth of cut. This quantitative influence for AISI D3 under CBN tools is a key outcome.
b) an optimized cutting condition (180 m/min, 0.06 mm/rev, 0.05 mm) produced the lowest surface roughness of 0.37 µm, demonstrating a stable shearing mechanism with minimal BUE.
c) a strong correlation between surface roughness

and fatigue life was established: smoother surfaces achieved significantly higher fatigue life (2.8×10^7 cycles).

d) the study distinguishes two mechanisms of white layer formation: 1) Thermo-mechanically driven phase transformation at lower cutting speed (120 m/min), 2) Thermal at higher speeds (150 & 180 m/min). This speed-dependent transformation mechanism is a notable contribution.

e) the results show that hard turning using CBN inserts provides a reliable finishing alternative for hardened AISI D3 steel while offering improved surface integrity and fatigue performance.

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