A Review of Surface Integrity issues for Quality and Productivity improvement in Hard Turning

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Abstract

Hard turning reduces the re-processing of the component thus it is an economic alternative to grinding, but its reliability is often unpredictable and challengeable. Reliability of hard turning surfaces mainly depends upon the surface integrity. Surface integrity factors i.e external and internal factors play a prominent role in the performance of the machined components. High service integrity delivers the good service performance of the component or vice-versa, thus the control of surface integrity is uttermost importance in hard turning processes. In this paper, an effort has been made to review the impact of cutting parameters on residual stress distribution and surface integrity factors such as surface roughness, microstructure, and micro-hardness in hard turning to brings out the comprehensive analysis.

Keywords: Surface integrity; Surface roughness; Residual stress; White Layer; Microstructures; Microhardness; Tool Life; Tool wear.

1. Introduction

Productivity has now become a common watchword. The manufacturers in the world are continuously identifying the higher productivity solutions to sustain the competitiveness of manufactured products [1]. High productivity refers to do the work in the shortest possible time with least investment on inputs without sacrificing quality, and with least wastage of resources i.e. the aim is higher quality, lower cost and less wastage. So, it is required to identify appropriate technological advancements that can help the manufacturing industry to improve the quality of the product and reduce the cost. It is known that 8-10 percent of material generated by machining processes goes to waste. By utilising better machining conditions and tools, this wastage can be reduced to an extent [2].

In manufacturing industries, practical knowledge, experience, and skill of supervisors are considered to assess the cutting conditions, cutting tools and tool geometries but, these cannot be accepted all the time. This irrational approach shows lower efficiency because of improper utilization of machine tool capabilities. This can be improved by carefully selecting the critical evaluating parameters to achieve the commanded responses within the constraints of low-cost production [3]. Any false decision in this; accounts for huge production cost and reduced product quality.

Although in the manufacturing industry continue advancement takes place but turning still leftover as the most significant process used for shaping the different materials because the conditions of operations are varied [2]. Turning focus on the features of the tool, input work material, output quality characteristics (or responses) and the cutting conditions which perform a significant role in the productive use of a machine tool [4]. The materials mostly required in the tooling applications have high wear resistance. Wear resistant materials are difficult to machine [1]. These wear resistance materials used in blanking or forming dies and thread rolling dies, shear blades and planer blades. The hard turning has the potential for improving the output quality characteristics of these wear resistance workpiece materials [5].

2. Brief Background

The article presents a brief background of hard turning, tool wear, tool life, and surface integrity.

2.1 Hard Turning

During the 1970s the work on hard turning was started and primarily gets its reorganization with the development of new advanced cutting tools [6][7]. These tools phase out the need for annealing and grinding since these are able to produce complex geometrical surfaces with precision [8][9].
Hard turning enables the manufacturers to machine hardened materials having hardness values typically in between the 58–65 HRC to obtain finished work pieces directly under dry conditions [9][10][11][12][13][14][15][17]. Even at smaller depth of cut and feed rates; the material removal rate is much greater than in grinding for some applications in hard turning [27] [10]. Thermal distortion takes place on the surface of work piece, due to the rubbing action of the grinding wheel, which allows high temperatures to penetrate deep into the work piece resulting in the formation of a white layer [1]. Hard turning drops the number of operations including rough turning, heat treatment needed to manufacture a component as shown in figure 1 and thereby utilizing the input resources effectively thus enhancing productivity [18].

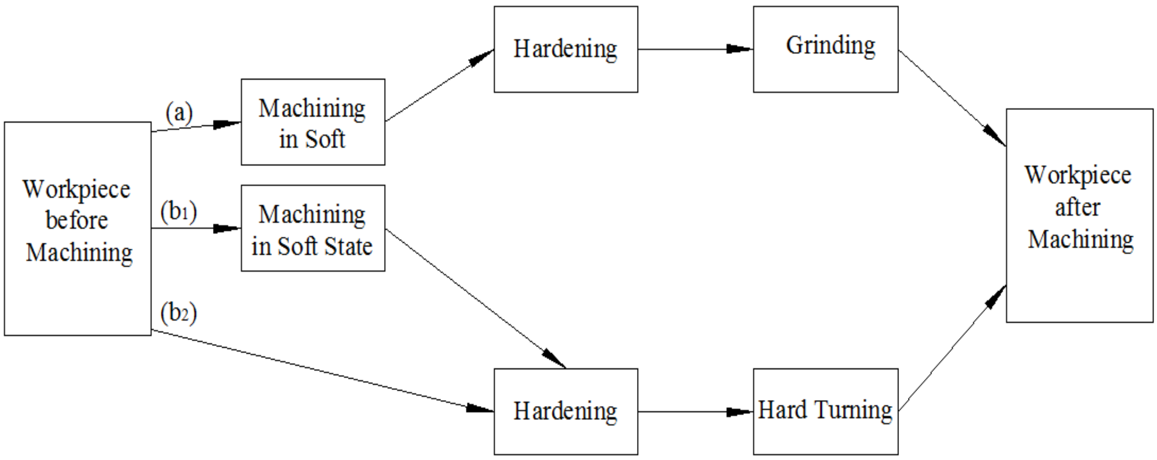

Fig.1. (a) Conventional turning and (b_1 and b_2) optimised turning process

2.2 Surface Integrity

Surface integrity have the prominent role in the mechanical performance of machined components [23]. Service performance of the component will be proportional to surface integrity. Thus the control of surface integrity is of substantial importance in machining processes and depends upon internal and external factors as shown in figure 2.

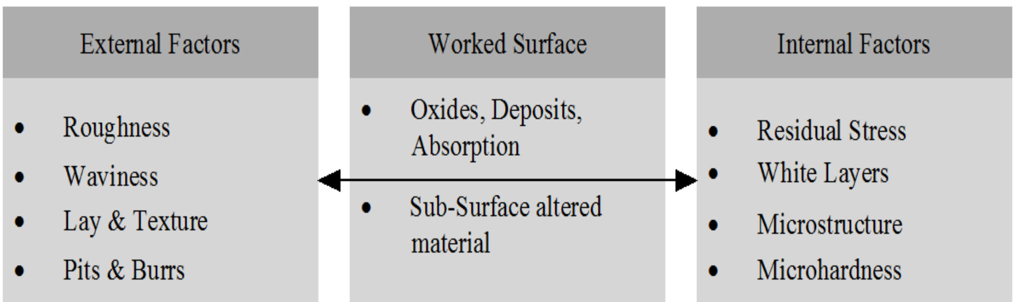

Fig. 2. Schematic diagram of worked (machined) surface

2.2.1 Residual Stresses

The tensile or compressive stresses remaining on the machined surface after the finishing process can be recognised as residual stresses [9]. The layers containing stresses may be deep or shallow depending on the process parameters, work piece and tool material [31]. In figure 3 the subsurface residual stress distribution characteristics curve in precision hard turning indicates characteristic conditions such as the maximal residual stress, the maximal residual stress depth (penetration depth) and effective residual stress depth (beneficial depth).

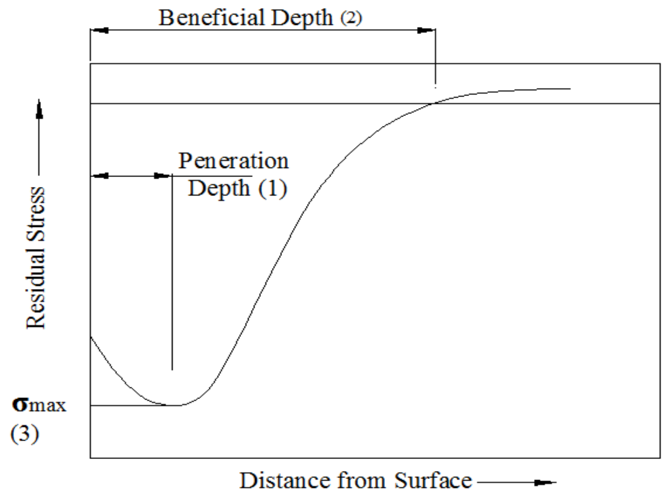

Fig. 3. Subsurface residual stress distribution curve [10][32]

Residual stresses plays the important role in component quality and life [33][31]. Thermoplastic deformation produced by cutting edge geometry generates tensile stresses which can lead to premature failure of components [31] [34] [35]. Generated or induced compressive residual stresses are usually improved the service quality, safety, component life, and performance of the machined work piece because they prevent crack nucleation.

2.2.2 Microstructures

A variety of emissions has been generated after the interaction of an electron beam in a vacuum chamber at the surface of solid specimens in SEM. The information provided by the emissions that derived from electron-sample interactions revealed about the surface topography, element crystalline structure, chemical composition, and orientation of materials making up the sample. It is important to study these variable as it directly impacts the specimen functionality, such as friction, wear, and fatigue [25].

The SEM is also able to perform the analyses of chosen point locations on the sample. In most applications, a small area over sample was focused ranging from approximately 1 cm to 5 microns in width, and a 2 – dimensional image displays spatial variations in the properties of scanned sample. It is also used to determine and understand the crystalline structure, crystal orientations and phase of materials [41].

3. Literature Review

Various studies have been performed by the researchers showing the effect of machining parameters such as feed, depth of cut, speed and tool geometry on residual stresses, microstructure, tool wear and surface roughness and their combinations in hard turning by using different workpiece materials. The summary of their work has been listed in table 1.

Table 1. Workpiece material, Cutting parameters, Tool material and Response parameters in Hard Turning

Journal Name	**Material**	**Cutting Parameters**	**Tool** (Single/ Multiple)	**Tool Material**	**Response Parameters**
International Journal of Advance Manufacturing Technology [5]	AISI 5115 (16MnCrS 5)	Feed/ Corner radius/ Depth of Cut	Single	WBN560 with a CBN content of 56% with different corner radius	Tool wear and Cutting forces
Journal of Materials Processing Technology [19]	AISI 52100	Speed	Single	CBN insert - grade BNC200	Cutting temperature & its correlation with white layer micro-structure & the residual stresses.

International Journal of Current Engineering and Technology [47]	AISI 52100	Feed/ Speed/ Depth of Cut	Single	Multicoated carbide insert (TiN-TiCN-Al_2O_3-TiN) under cryogenic cooling conditions	Cutting forces
International Journal of Advance Manufacturing Technology [46]	AISI 52100	Feed/ Speed/ Depth of Cut (Parameter fixed)	Single	CBN10 with 50% of CBN grit	Flank wear and Cutting forces
International Journal of Advance Manufacturing Technology [18]	AISI 52100	Speed/ Feed/ Nose radius/ Rake angle/	Single	Mixed ceramic inserts of different geometry	Surface roughness
International Journal of Advance Manufacturing Technology [48]	AISI 52100	Speed/ Feed/ Nose radius/ Chamfer angle	Single	Mixed ceramic inserts of different geometry with solid lubricants	Surface roughness
Journal of Materials Processing Technology [10]	AISI 52100	Feed/Speed/ HRc/ Chamfer-Hone	Single	CBN	Residual stresses
Journal of Materials Processing Technology [49]	AISI 52100	Rake angle/ Feed/ Depth of Cut.	Single	CBN100 with different geometry (Rake angle)	Residual stresses
Journal of Materials Processing Technology [34]	AISI 52100	Feed/ Speed/ Depth of Cut / Nose radius	Single	CBN tool (TiC & Al_2O_3) with different nose radius	Tool wear, Cutting forces and Residual stresses
Journal of Manufacturing Processes [50]	AISI 52100	Hardness/Feed/ Chamfer edge / Hone edge	Single	PCBN inserts with three types of edge preparation	Residual stresses and Microstructures
Journal of Materials Processing Technology [44]	100 Cr 6	Feed/ Speed/ Depth of Cut	Single	CBN7020	Surface roughness, Tool wear, Cutting force & Chip volume
Journal of Materials Processing Technology [36]	AISI 52100	Feed/ Speed/ Depth of Cut	Single	CBN	Residual stresses
International Journal of Advance Manufacturing Technology [51]	AISI 52100	Feed/ Speed/ Depth of Cut (All parameter fixed)	Single	PCBN tool with low CBN contents (50%) & ceramic (TiAl) as binder	Surface roughness, Tool wear and Cutting forces
Procedia Engineering, CIRP 1(2012) 494 - 499 [13]	AISI 52100	Speed	Single	CBN inserts of grade BNX10	Cutting forces, Tool wear, Residual stresses and Microstructure
Indian Journal of Applied Research [22]	AISI 52100	Feed/ Speed/ Depth of Cut	Single	Coated carbide insert under cryogenic cooling conditions	Surface roughness and Microhardness
Elsevier, Procedia Engineering, 6 (2014) 1233 – 1242 [52]	AISI 52100	Feed/ Speed/ Depth of Cut	Single	Multilayer coated carbide insert	Tool - chip interface temperature
Precision Engineering [53]	AISI 52100	Feed/ Speed/ Depth of Cut	Single	CBN insert	Surface roughness, Micro structural analysis, Residual stresses and Chip morphology
Materials Today: Proceedings 2 (2015)	AISI 52100	Speed	Single	PCBN	Temperature measurement

1907–1914 [54]					
Materials Today: Proceedings 2 (2015) 3268–3276 [55]	AISI 52100	Feed/ Speed/ Depth of Cut	Single	PVD coated nano-laminated carbide inserts (TiSiN – TiAlN)	Plowing cutting forces and Chip morphology
Science Direct Acta Materialia [39]	AISI 52100	Speed	Single	CBN insert	Microstructures of different types of White layers
International Journal of Advance Manufacturing Technology [56]	AISI 52100	Feed/Speed/HRc/ Depth of Cut/ Tool material	Multiple	High CBN & Low CBN	Tool life
American Journal of Engineering and Applied Sciences [15]	AISI 1020	Feed/ Speed/ Depth of Cut	Single	CNMG 432TT5100 Carbide insert	Surface roughness and Temperature
Journal of Materials Processing Technology [37]	AISI 1045	Feed/ Speed/ Side cutting edge angle	Single	CVD Coated Carbide Tools with different Side cutting edge angle	Surface roughness and cutting force
International Journal of Machine Tools & Manufacture [41]	AISI 1053	Feed/ Speed/ Depth of Cut/ Rake angle (All parameter were fixed for both tools)	Multiple	CBN particle coated tools and solid PCBN tool	Residual stresses, Microstructure and Microhardness
Wear [9]	AISI 4340	Feed/ Speed/ Depth of Cut	Single	Al_2O_3 insert	Tool life, Residual stresses, Cutting force, Microstructure using simulations.
Science Direct Proceedings 2 (2015) 2615–2623 [45]	AISI 4340	Feed/ Speed	Multiple	Uncoated carbide tool and TiN coated carbide inserts	Surface roughness and Tool wear
Tribology International [59]	AISI 4340	Feed/ Speed/ Depth of Cut	Single	Polycrystalline cubic boron nitride (PCBN) tools	Tool wear and Tool life using acoustic emission
Journal of Materials Processing Technology [60]	AISI 4340 (Continuous, Semi-interrupted and Full interrupted surfaces)	Feed/ Speed/ Depth of Cut/ Cutting edge geometry: Chamfered and Edge rounding. (All parameter were fixed for both tools)	Multiple	**CBN** Low CBN 7020 and High CBN 7050	Tool wear and Tool life
Journal of Materials Processing Technology [7]	AISI 4340 (Continuous and Interrupted surfaces were taken)	Speed as recommended by the manufacturer for each tool	Multiple	**CBN** Low 7015 and High 7025 **Ceramic** CC670 & CC650	Tool wear and Tool life
Journal of Achievements in Materials and Manufacturing Engineering [61]	AISI 440C	Feed/ Speed/ Depth of Cut	Single	CBN	Surface roughness and Tool wear

Wear [27]	AISI 5140	Feed/ Speed/ Depth of Cut	Multiple	Mixed ceramic inserts (71% Al_2O_3, 28% TiC and 1% other) and Wiper insert	Surface roughness and Tool wear
Journal of Materials Processing Technology [17]	AISI D2	Feed/ Speed/ Cutting time	Single	Wiper mixed alumina ceramic inserts with TiN coating	Surface roughness and Tool wear
Procedia Engineering, 97 (2014), 338–345 [6]	AISI D3	Feed/ Speed/ Depth of Cut	Single	Al_2O_3/TiC mixed ceramic tool	Tool wear
International Journal of Refractory Metals and Hard Materials [12]	AISI D6	Feed/ Speed	Single	PCBN tools in the form of inserts (CB7015 of CBN with PVD TiN coating and ceramic binder)	Surface roughness, Cutting force and Tool wear
Elsevier, Procedia Engineering, 97 (2014), 241–250 [4]	Aluminum	Feed/ Speed/ Depth of Cut	Single	Tungsten carbide	Surface roughness, Cutting force, Tool wear, MRR and Power consumption
Measurement [20]	Al 7075	Feed/ Speed/ Depth of Cut	Single	Single point diamond tool with different nose radius	3D Micro topography and Tool wear
International Journal of Machine Tools & Manufacture [31]	S.S. - 304 Steel – 37 Al alloy 2024 Al alloy 7001 Brass	Feed/ Speed/ Tensile strength		Not Mentioned	Residual stresses
Elsevier, Procedia Engineering, 51 (2013) 781-790 [62]	Carbon Fiber Reinforced Polyester Material	Feed/ Speed/ Depth of Cut	Single	CBN	Surface roughness
International Journal Advance Manufacturing Technology [63]	Brass C26000	Feed/ Speed/ Depth of Cut	Single	CNMG 120408 insert	Surface roughness
Procedia CIRP 13 (2014), 219 – 224 [40]	CoCrMo alloy	Feed/ Speed	Single	Single layer PVD coated TiAlN carbide tools	Surface finish, Microstructure, Microhardness and Residual stresses
International Journal Advance Manufacturing Technology [25]	GCr15 steel or SAE52100	Feed/ Speed	Single	PCBN tools (7015)	3D Micro topography and Cutting forces
International Journal of Engineering Research and Applications[42]	H11	Tool material/ Feed/ HRC/ Speed	Multiple	High CBN, Low CBN, Mixed ceramic	Tool wear
International Journal of Machine Tools & Manufacture [38]	H13	Speed/ Depth of Cut	Single	CBN	White layer, Tool wear, Temperature measurement and Microstructure

International Journal Advance Manufacturing Technology [8]	H13	Feed/ Speed	Single	CBN	Cutting forces and Temperature measurement
Journal of Materials Processing Technology [64]	Inconel 718	Feed/ Nose radius/ Entry angle	Single	Coated tungsten carbide inserts with a multilayer coating	Residual stresses, Cutting forces, Surface roughness, Tool wear and Microstructure analysis
Measurement [35]	Inconel 718	Feed/ Speed/ Depth of Cut	Single	Cemented carbide inserts	Residual stresses
Procedia CIRP 3(2012) 370–375 [65]	Inconel 718	Feed/ Speed	Multiple	**PCBN Tools** Uncoated and TiN Coated tools	Cutting forces, Tool life, Tool wear mechanisms and Surface integrity
Wear [43]	Inconel 718	Speed/ Side cutting edge angle	Multiple	Carbide substrates (CP500 and TS2000)	Cutting forces, Surface roughness and Tool wear
Journal of Materials Processing Technology [16]	MDN250	Feed/ Speed/ Depth of Cut	Single	Coated ceramic inserts	Surface roughness and Cutting forces
Research Journal of Recent Sciences [26]	Mild Steel	Feed/ Speed/ Depth of Cut	Single	High speed steel tool	Tool wear and Surface roughness
CIRP Annals - Manufacturing Technology 62 (2013) 67–70 [33]	Not Defined	Feed/ Speed/ Depth of Cut	Single	PVD-coated carbide cutting tool	Residual stresses
Science Direct Manufacturing Letters 2 (2014) 112–117 [66]	Not Defined	Feed/ Speed/ Depth of Cut (All parameters were fixed)	Single	Smart turning tool embedded piezoelectric film sensors	Cutting forces
International Journal Advance Manufacturing Technology [11]	H 13	Feed/ Speed/ Depth of Cut (All parameters were fixed)	Multiple	Ultrafine-grained ceramic and Common ceramic tool	Simulation results were used to explicate the differences of wear mechanism for different tools.
Journal of Materials Processing Technology [67]	SS202	Feed/ Speed/ Depth of Cut	Single	Carbide insert tool under cryogenic cooling conditions	Tool wear and Cutting forces
Elsevier, Procedia Engineering, 63 (2013), 796 – 803 [69]	UNS A92024 alloy	Feed/ Speed/ Depth of Cut	Single	Uncoated WC-Co inserts	Surface roughness and Ultimate tensile strength (UTS)
Elsevier, Procedia Engineering, 63 (2013), 20 – 28 [23]	Elektron-21 wrought Mg-Zn-Zr-RE alloy	Feed/ Speed/ Nose radius (All parameters were fixed)	Single	Carbide inserts with different nose radius	Residual stresses, Surface roughness, Microstructure and Microhardness

4. Discussion and Conclusion

Table 1 shows the number of articles reviewed on various output parameters and from the reviewed articles following conclusion could be drawn:

Most of the literature has revealed that researchers have attempted their study with bearing steel with the single insert of tool material. Very few researchers reported on cold work tool steel AISI D3 with different input and output parameters so far. It displays excellent abrasion resistance and has good dimensional stability and high compressive strength. In the hardened condition, its machining should be limited due to its abrasion/wear resistance.

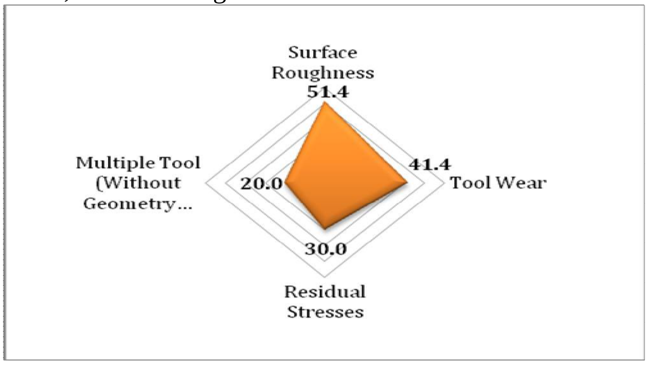

Fig. 4. Number of parameters (%age) used in hard turning

It is heat treatable and will contribute hardness in the range 58-64 HRC. It finds its applications in rolls for cold strip mills, wire squeezer mills, forming rolls, dies for small metal parts, blanking and forming dies, press tools, tile mould liners, master hobs for cold hobbing and sleeves for corrosive powders. Fig. 4 shows that only 20% researchers use multiple tools in their research, and 51.4% has analysed the surface roughness.

Fig. 5 indicated the multiple combinations of parameters employed in various articles by researchers on hard turning. It has been found that 21.4% researchers focused on surface roughness and tool wear and surprisingly only 3% used multiple tools to evaluate surface roughness, tool wear and residual stresses togeather.

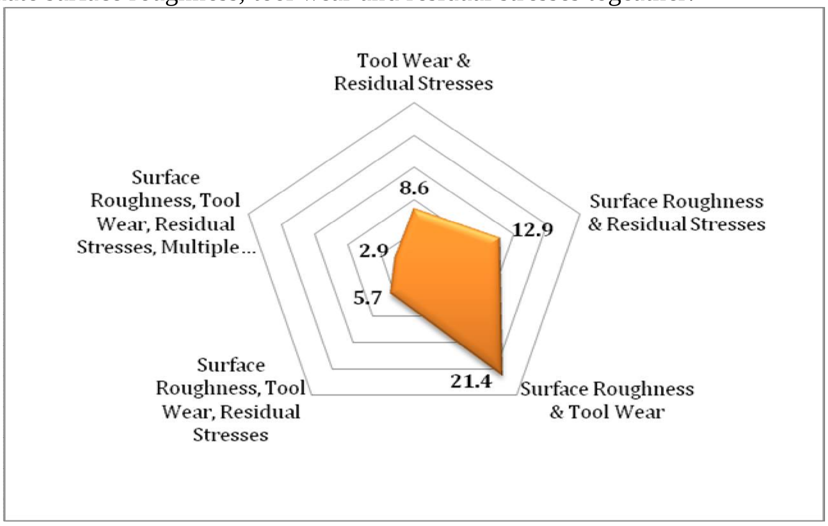

Fig. 5. Multiple combination of parameters (%age) used in different articles

The literature revealed that the information concerning residual stresses of the machined surface region would be valuable in the design and manufacture of parts. Therefore, it is important to determine the effect of the machining process parameters on the residual stress profile with different tool in AISI D3 tool steel and subsequently, prefer those machining parameters which may enhance fatigue life by inducing favourable residual stress (compressive stress).
Detections and minimization of machining variables such as residual stress, tool wear, etc. are the burning issues which need to be investigated. Hence it became imperative to provide suitable cutting parameters for different tool work material combinations, to enhance the overall productivity of the manufacturing industries.
Numbers of theoretical models have been devised and presented by researchers to establish a relationship between cutting parameters and machining variables. The machine tool structure and cutting process dynamics, however, are so complex that these theoretical models cannot be fully relied upon. There is also a need for models which could consider the number of machining variables at different cutting parameters so as to provide optimised results. With this view, it is important to investigate the characterization of surface integrity with low and high-grade CBN cutting tools to determine the internal and external factors such as residual stress, microstructure, tool wear and surface roughness.

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