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Continuous and Interrupted Hard Turning Using CBN-L Tools at Moderate Cutting Speeds

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***Abstract*—The objective of this experimental work is to find a suitable tool and suitable cutting condition for reconditioning of hot forging dies and thread rolls. Turning experiments were carried out at constant feed and depth of cut but at different low and medium cutting speeds on interrupt and continuous work surfaces using low content cubic boron nitride tool. The machining experiments showed that the tool life is very sensitive to work-piece geometry i.e. it performs better in medium cutting speeds (102 m/min) on interrupted surfaces and tool life proportionally reduces on continuous surface (102 m/min) due to thermal shocks. At a very low speed of 60 m/min the CBN-L tools are prone to chipping of the cutting edge in continuous turning and mechanically failure in interrupted turning. Scanning Electron Microscopy (SEM) micrographs suggested chipping of cutting edge, micro-fracture and crater wear to be the different types of tool wear occurring in CBN tools.**

***Keywords*— Hard Turning; Continuous; Interruptions; Abrasion; Adhesion; Chemical Dissolution; Chipping; Crater; Tribo-Chemical Wear;**

I. INTRODUCTION

In the quest of keeping a low maintenance cost of the dies and thread rolls, the typical problem which arises on the cutting edges of such tools in continuous cutting is development of wear. On the other hand a low speed interrupt cutting results in breakage of tool insert by impact and in high speed interrupt cutting the breakage is caused by the fast growth of crater wear. Moreover, in heavy interrupt cutting as the stress on the cutting edge increases, tool life becomes more unstable and shorter. As a result, there is little cost advantages of cutting with CBN tools, and grinding continues to be the primary method of heavy interrupted machining. In hard turning the inserts are subjected to undesirable thermal and mechanical shocks, in addition to that the interrupted surfaces interject specific excitation amplitude into the machining system, which is undesirable and needs a rigid and properly damped machining system.

To meet this demand, CBN inserts are tough enough to handle such demanding situation. machining. Recently, demand for lower machining cost has grown in heavy interrupted cutting and tougher material like CBN meet the challenges. Since CBN-L (Low content cubic boron nitride) tools are cheaper than CBN-H (High content cubic boron nitride) tools, the current study investigates the suitability of using CBN-L tools to turn at low and moderate speeds for both continuous and interrupt machining to realize both technological feasibility and economic viability

Historically, researches in interrupt cutting have lot to offer in terms of the material aspect of the cutting tool more so when the behaviour of the CBN tool grades varies accordingly to their grain size, CBN content, binder material and also owing to their different thermal properties. There are two grades of CBN tools i.e. CBN-H and CBN-L (Sandvik Coromat, 1994) with different mechanical and thermal properties. Literature study shows that CBN-H has longer tool life compared to CBN-L during machining of hardened heavy interrupted surfaces because of their high hardness and CBN-L requires medium speed on semi-interrupted surfaces for longest tool life [1]. CBN-L tools are more successful in machining continuous and less interrupted work surfaces and are not suitable for heavy interrupted surfaces [2] since in CBN-L tools the CBN content is less i.e. the CBN content is replaced by ceramic binder, which results in loss of hardness along with toughness but there is improvement of chemical stability. However, the wear resistance of CBN-L grade is very high, despite lower hardness, which is a puzzling phenomenon. But the finer grain size of CBN particles of CBN-L inserts attribute to high wear resistance, high hardness and high transverse rupture strength.

The longer tool life of CBN-L can be attributed to greater bond strength of the ceramic binder with the CBN particles, protection from further wear by the adherent layer (protection effect) formed during machining, while the welding layers, on the tool flank wear land of CBN-L, lower thermal conductivity of CBN-L leads to resultant softening of workpiece in the shear zone. Experiments have been conducted to study the feasibility of machining hardened work surfaces with no interruption, semi-interrupted and highly interrupted using CBN-H and CBN-L tools. It was found that the CBN-L tools with low toughness have a tool life similar to CBN-H and can withstand the shocks of interruption [3]. Evaluation of surface integrity and machinability in terms of tool wear showed that the CBN-L had better machinability and is superior to CBN-H [4].

An experimental investigation [5] was done on reconditioning of dies of hot forging using carbides, ceramics and CBN-H. Carbides performance was appreciable at low speeds and low feeds and ceramics did not perform better in all cutting condition. There was drop in performance of CBN-H tools at low speeds but at high cutting speed the performance improved. In the present work, the high cost per cutting edge has been considered for the choice of CBN-L as cutting tool material which is cheaper and superior as compared to CBN-H. The study focuses on machining hardened damaged layer of hot forging dies (continuous cutting) and damaged threads of the thread rolls (interrupt cutting) at speeds ranging from low to medium. Various mechanisms of tool failure in machining damaged as well as fresh surfaces during continuous and interrupt cutting have also been investigated with the help of SEM.

II. Research Motivation

Reconditioning of rolls and dies are suitable examples of continuous and interrupted turning. Form tools like thread rolls, knurling tools, dies used for stamping and hot forging, hot extrusion dies, press tools etc. work on extremely aggressive tribological systems. Micro and macro dents on the hot working die surfaces (with depth upto 1 mm), damaged threads on thread rolls and dull cutting edges on knurl tools are seen at the end of the die tool life. Tools and dies are scraped because of uneconomical machining cost or brought to use by reconditioning. Thread rolls after reaching the end of their useful life require reconditioning either by grinding or by turning in hard condition to produce fresh surface.

Hot forging die faces are hard turned to remove the micro and macro grooves. Dies and form rolls are converted and brought to use by increasing the internal diameter or turning the outer formed surface. Such turnings are extremely difficult because of the high impact forces generated due to interruption of the cut by the grooves on the die surface or damaged threads on the thread rolls or due to hardened layer on the die surfaces. A similar experiment was conducted by Sales et al. [5] for reconditioning of dies to investigate the performance of carbides, ceramics and CBN-H, were they did not consider the CBN-L tool. This study is done with an aim to explore the suitability of using CBN-L tools as an economical mean for maintenance of hardened dies or form tools. Turning experiment were carried out at constant feed and depth of cut but at different low and medium cutting speeds for both interrupt and continuous machining to affirm an economical method of maintenance of form tools and forging dies and to identify a suitable CBN-L tool [6].

III. Experimental Details

A. *Selection of Tool Material*

Based on the Sumitomo catalogue, a CBN- L insert of BN300 grade, applicable for both continuous and interrupt cutting of hardened steels was selected for the experimental study. The mechanical and thermal properties of this grade are given in Table 1. Cutting inserts with ISO code 2NU CCGU 09T308 were 80^o rhombus shape tungsten carbides substrates brazed with 0.1 mm × 30^o chamfered CBN tips; cutting geometry was 6^o rake angle, 6^o relief angle, 0.8 mm nose radius.

TABLE 1
Thermal and mechanical properties of CBN-L

CBN Grade	BN-300	**Hardness**	3300-3500 HV
Binder	TiN	**Transverse Rupture Strength**	110-120 Kg/mm^2
CBN %	60	**Fracture Toughness**	4.0 MPa (m)$^{0.5}$
Grain size	0.5 µm	**Thermal Conductivity**	54 W/mK.

B. *Work Material Machining*

Two different workpiece geometries (AISI D6 Tool Steel) were machined before hardening and tempering for two different tests.

For continuous machining, the workpiece of Ø 42 mm × 160 mm length cylindrical bars as shown in Fig. 1 (experimental machining set-up) were used whereas for interrupt machining the workpiece with 6-slots were prepared by milling slots of 6 mm width and 8 mm depth on Ø 42 mm tool steel bar of length 160 mm as shown in Fig 2 (interrupted machined workpiece).

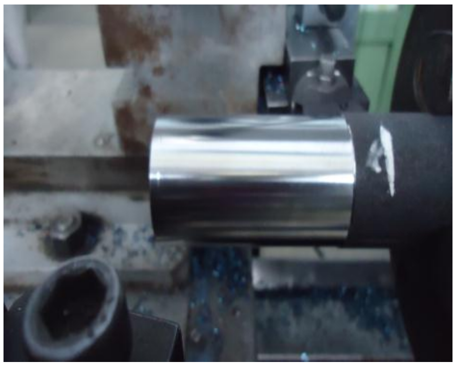

Fig. 1 Continuous Surface

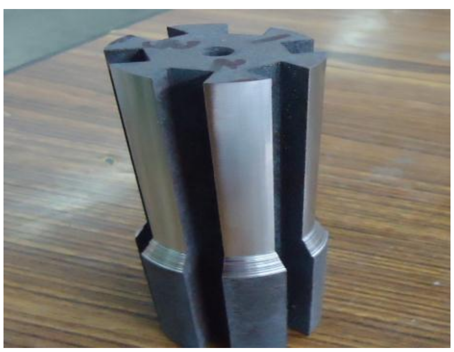

Fig. 2 Interrupt Surface

C. Heat Treatment

All work material converted into various test specimens was annealed to remove any preexisting anomalies of material properties. Since all are machined component and hence required preheating before hardening and tempering. Since the steel has to be through hardened or are to be heated to the austenitizing temperature range must be annealed prior to allotropic transformation. This is a "given" in the heat treatment industry, since cracking upon rapid heating may occur if a pre-heat annealing operation is not performed.

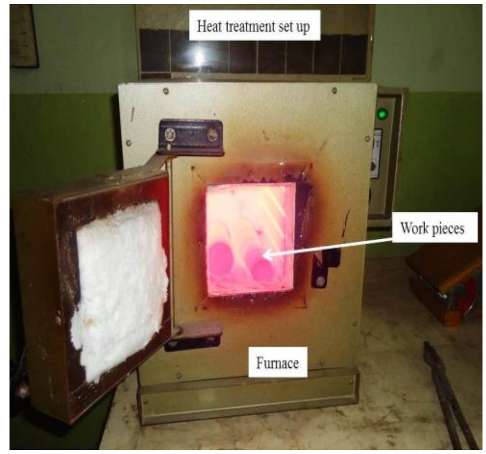

Fig. 3 Heat treatment set-up for hardening and tempering

The standard procedure followed for heat treatment using a set up as shown in Fig. 3 are as follow:

Annealing (step-1)

- Preheating to 200^{o}C; hold for 30 min.
- Slow (stepwise) heating from 250^{o}C to 450^{o}C than to 700^{o}C and finally to 900^{o}C; holding for 1 hr at each step.
- Holding for 2 hr at 900^{o}C.
- Slow Cooling; furnace shutoff leaving samples inside to cool to room temperature.

Austenitizing (Step-2)

- Heat the furnace to 250^{o}C; samples loaded into the furnace
- Slow (stepwise) heating to preheat temperatures; 250^{o}C to 450^{o}C to 750^{o}C; hold for 90 min at to 750^{o}C.
- Slow (stepwise) heating from preheat temperatures to austenitizing temperature; 750^{o}C to 850^{o}C to 970^{o}C; hold for 2 hrs at to 970^{o}C.

Quenching (Step-3)

- After holding for 2 hrs, the furnace is shutoff and the door is opened to cool inside the furnace until red heat is gone.
- Samples were removed and air cooled to a temperature of 50^{o}C in still air

Tempering (Step-4)

- A separate furnace was used for tempering as the tempering was done immediately after quenching. The second furnace was set aside at a desired tempering temperature of 250^{o}C.
- Loading the samples inside the furnace immediately after they reach 250^{o}C and holding for 2 hrs
- Samples removed from the furnace and allow them to cool to room temperature in still air.

The experimental work was done on the workpiece bars after turning the outermost oxidized layer by 1 mm for removal of any scales formed during heat treatment, which could otherwise have an adverse effect on the experimental results.

D. Experimental Procedures

Hard turning experiments were carried out on DRO lathe (Model: Bajaj-Pioneer-175 Geared Headed), 8-spindle cutting speed (8-1200rpm) and 24 no: of feeds. Surface roughness measurement were made offline using a surface roughness tester (SJ-301 Mitotoyo, Japan), X-axis (drive units) with measuring range of 12.5µm. Continuous machining and interrupt machining tests were conducted at two different cutting speeds of 60 and 102 m/min at a constant depth of cut of 0.1 mm and a feed rate of 0.13 mm/rev. This cutting condition represents machining at low and medium speeds to ensure that the tool wear is not rapid, for achieving low tooling cost and sufficient material removal which is critical for reconditioning of dies and rolls. Moreover, the selection of feed values and depth of cut was made with an objective to obtain surface quality and stock removal equivalent to that obtained in grinding. This surface roughness criterion is also used because surface finish of 3 µm on the roll surfaces or on the die surface is required for their reuse in industry applications. The two types of work surfaces prepared were turned to 75 mm length in a single pass. One single pass had an interaction cutting time of 3.15 minutes. A maximum of 20 passes were used on each type of workpiece surface at different cutting speeds. Fresh inserts were used for each cutting speed. The machining test was terminated until a fresh insert failed due to chipping/fracture or produced surface roughness greater than 3 µm. The surface roughness of the work surface was measured at regular interval of 17- 20 mm space along the feed length after each pass to find out the change of surface roughness due to tool wear.

Minimum of 9 surface measurements after each pass at 120^{o} and total of maximum 180 observation of surface roughness were made for each cutting speed. The worn tools were then evaluated using SEM to identify the best suitable cutting condition for good CBN-L tool performance.

IV. RESULTS AND DISCUSSIONS

A. Interrupt Machining

Interrupt machining tests were performed using fresh inserts at two different speeds of 60 and 102 m/min at a constant depth of cut of 0.1 mm and a feed rate of 0.13 mm/rev. The surface roughness R_a values measured were in the range of 0.48 – 1.15 µm up to four number of passes for both the speeds. Later on the surface finish obtained at lower speed (60m/min) deteriorated at faster rate as compared to the surface finish obtained while machining at a speed of 102 m/min. The maximum surface roughness value obtained during machining at 102 m/min was 2.0 µm after 20th pass and no chipping of cutting edge was observed as shown in Fig. 4 and the brazed CBN tip was intact. This finding shows that the cutting condition is adequate enough to enable the tool to sustain the toughness required during shock loads and prevent the growth of tool edge radius due to chipping and affect surface roughness. This shows the resilience of CBN-L tools to chipping and fracture at low speeds. Although crater initiation started after higher number of passes but no complete crater formation was observed as shown in Fig. 4. Crater wear is smaller in interrupted cutting than continuous cutting [3]. The cutting edge sustained up to 20 numbers of passes without any effect on the nose radius giving the desired surface finish. At a low speed of 60 m/min high surface roughness values were obtained immediately after 4th pass because of the affected cutting edge due to mechanical impact load of the interruption. The test was terminated due to extremely poor surface finish. The stress condition on the cutting edge is uncomplimentary at such a low speed and results in gross failure. At low speeds the wear of CBN tool is more mechanical than thermally induced [1]. In this experiment the tool failed due to loss of the supporting shim base where the tool tip is brazed as shown in Fig. 5 and the failure is only attributed to the gap between the properties of the shim base and CBN tool tip material [7].

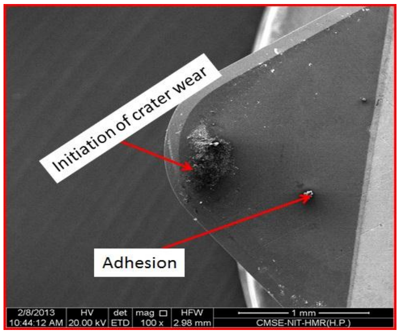

Fig. 4 Interrupt machining at 102 m/min and 20 passes

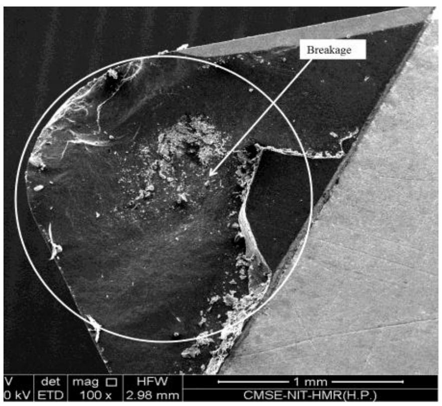

Fig. 5 Interrupt machining at 60 m/min and 10 passes

B. Continuous Machining

The observation was made on the performance of the CBN-L tool at cutting speed of 60 and 102 m/min, keeping the depth of cut 0.1 mm and feed rate of 0.133 mm/rev constant. Initialization of the crater wear on the rake surface begins immediately and the crater develops as shown in Fig. 6 and extended until it reaches the preceding flank wear. At low speed range this phenomenon weakens the tool nozzle and collapse of the nose is inescapable suggesting these tools are not a good performer for continuous machining below 100 m/min. The nose cutting edges degraded on each subsequent passes more so after four passes. The surface roughness (R_a) measured on the machined surfaces were in the range of value of 0.53 - 2.67 µm initially with fresh inserts at both the speeds.

After four passes the surface roughness value exceeded 3.0 µm suggesting the poor performance of CBN-L and its susceptibility to high wear promoted by chipping at a low cutting speed. CBN-L performs better at a speed range of 150-180m/min [8]. During initial passes the tool experienced chipping on the cutting edge and crater wear on the rake face as shown in Figs. 6 and 7, the chipping and the crater increases after each subsequent passes i.e with increased interaction time between tool and work material. The tool experienced a larger crater wear after higher number of turning passes, broke off completely from the edge due to highly localized plastic deformation.

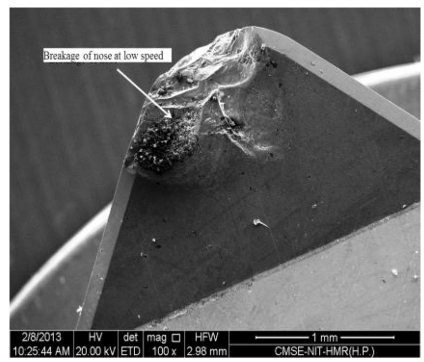

Fig. 6 Continuous machining at 60m/min and 15 passes

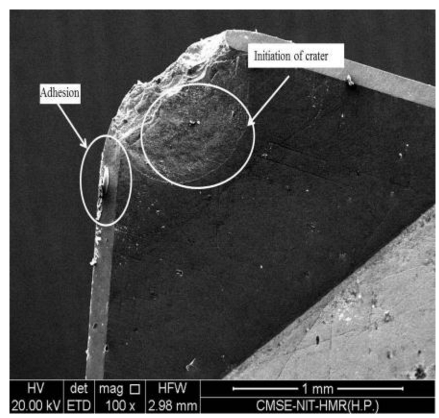

Fig. 7 Continuous machining at 102 m/min and 20 passes

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V. CONCLUSIONS

The major conclusions drawn from this research study are:

1. It can be suggested that the chamfered CBN-L tool: Grade-BN300 with 60 % CBN content and 0.5 µm grain size are suitable candidate for machining hardened damaged layer of hot forging dies and damaged threads of the thread rolls, provided the cutting speed is kept at medium range of 100-120 m/min for removing the interrupt surfaces and at a little higher cutting speed of 150 m/min during continuous machining to obtain longer tool life [3]. A 0.5 µm grain size is appropriate as increased CBN grain size of 1µm and 3µm decreases the wear resistance. Both bulk hardness and transverse rupture strength remains high due to small grain size [1].
2. CBN-L tools perform better in terms of surface finish during interrupt machining at a speed of 102 m/min (below 2.0 µm upto 20th passes), whereas at the same cutting speed, the surface roughness value exceeded 2.0 µm after 4th pass in continuous turning. Although the CBN-H tools have good mechanical properties compared to CBN-L tools [1], the chamfered CBN-L (60 % CBN and 0.5µm grain size) is more resilient to mechanical wear and resists chipping and fracture of cutting edge during interrupted turning at 102 m/min. The result shows the CBN-L is better in terms of tool wear and surface finish for interrupted hard turning , which agrees well with the previous research [4]
3. It can be concluded that the tool life of CBN-L tools is very sensitive to workpiece geometry i.e. it performs better in cutting speeds on interrupted surface (102 m/min) and tool life proportionally reduces on continuous surface (102 m/min) due to thermal shocks. The CBN-L tool fails (gross fracture) due to mechanical shocks at 60 m/min during continuous and interrupted turning.

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