High Stock Removal Hard Turning of Hardened 52100 Steel with High-Pressure Coolant Applied

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Abstract. Hard turning experiments were conducted on hardened 52100 steel utilizing high-pressure (10.3 MPa) coolant. CBN inserts were used. The cutting conditions were investigated to obtain high stock removal with a feasible tool life on the large part hard turning process. A small thermocouple was mounted in a ground slot underneath the CBN insert tip, close to the cutting edge, to effectively measure the insert’s temperature during cutting. The cooling effect of the high-pressure coolant was evaluated by monitoring CBN insert crater wear and the time for the edge to become prematurely fractured. The temperature measurements show that the high-pressure coolant cools the insert more efficiently and has better lubrication capability leading to longer cut time without edge fracture. The study revealed that conventional low-pressure (0.4 MPa) coolant could not economically achieve high stock removal hard turning due to high cutting temperature leading to premature fracture of the cutting edge. When using the high-pressure coolant and the optimized parameters, the tool life was enhanced by nearly 100%. The machined surface microstructure did not degrade even with the generation of very high shearing and friction heat energy in the cutting zone. Based on validation cut results and production part cycle assessment, the application of high-pressure coolant enables feasibility of high stock removal in hard turning with the ability to improve the productivity of large part rough stage turning by about 46%.

1. Introduction
52100 steel is widely used in the manufacturing industry because it can easily and cost-effectively be through hardened during heat treatment to get the necessary or desired hardness. After hardening and tempering, the material’s microstructure transforms from austenite to tempered martensite and can attain hardness up to 58–62 HRC. Compared to carburized hardened microstructures, through-hardened tempered martensitic microstructures contain relatively large size, high-density, hard carbide particles. During hard turning of 52100 hardened steel, these hard carbide particles act very abrasively, like a grinding wheel’s abrasive grains, and can produce the same scratch effect on the tool and chip interfaces as grinding did. The friction heat generated at the tool and chip interface when they slide against each other under high contact pressure is one of the largest contributors to the acceleration of the cutting tool’s edge failure [1].

Over the authors’ many years of experience with hard turning practices, they have seen that 52100 hardened steel is much more difficult to machine because cutting tool wear occurs so quickly, making its application in large part hard turning less economical or not feasible, since this reason the grinding is still dominant even the hard turning has the advantages of quick setup, process very flexible. The goal of the study presented in this paper is to examine ways in which 52100 steel’s hard turning capability can be improved to expand its usefulness in large part hard turning. The authors propose the common-sense approach that could be achieved by applying high-pressure coolant to remove the...
additional heat and enhance the cooling effects to lengthen tool life. Pigott [2] was the first to consider this idea. He conducted tests using high-pressure coolant in steel turning with high-speed tools. He applied coolant at a pressure of 2.76 MPa directly on the flank face clearance. This cooling enhancement significantly increased the high-speed steel tool life. More recently, Mozammel Mia and Nikhil Ranjan Dhar [3,4] studied hard-turned EN-24T hardened steel using 80 bar high-pressure coolant and found that because the high-pressure coolant increased the cutting zone interface’s cooling efficiency and lubrication, the machined material surface roughness was significantly improved, and tool wear was reduced to the point that a carbide insert could be used in hard turning applications. Rosemar B. da Silva et al. [5] assessed the tool life of PCD tools when turning Ti-6Al-4V alloy using conventional and high-pressure coolants. They found that tool life increased when coolant pressure was increased to 15 MPa. However, when pressure was increased beyond 15 MPa, the opposite trend was observed. They therefore proposed that an optimized coolant pressure region existed which was related to the total heat generated during the machining. Akira Hosokawa [6] recently studied turning in difficult-to-machine stainless steel with high-pressure coolant; he found that in lower cutting speed ranges, the high-pressure coolant had more cooling effect than in high cutting speed ranges, and the coolant’s effectiveness in reducing chip breakage became significant only when the pressure was increased to over 7 MPa.

All these studies and investigations indicate that using high-pressure coolant to assist in machining can provide benefits such as longer tool life, higher machined surface quality and reduced chip breakage. However, all the published works were lab tests, and it has not been demonstrated in production that using high-pressure coolants can significantly extend the length of the high stock removal hard turning cutting time. Additionally, a high rate of stock removal requires longer tool life during cutting, but the conventional coolant pressure (0.4 MPa) cannot extend tool life sufficiently.

This paper presents an experimental investigation of high stock removal hard turning with high-pressure coolant applied. A small thermocouple was mounted in a ground slot underneath the CBN insert tip, close to the cutting edge, to measure the insert temperature in process to evaluate the cutting and cooling capability of the high-pressure coolant. Machining experiments were conducted using CBN inserts under different cutting conditions that led to a high stock material removal rate. The cooling capability was evaluated by monitoring cutting temperatures, tool life extension, the capability of chip breakage and process feasibility. Conventional low-pressure (0.4 MPa) coolant cutting was tested first as the benchmark for identification of the current process limit and tool failure mode, and then experiments on the three primary cutting parameters (speed, feed and depth of cut) were performed to establish optimization conditions. The optimization conditions were validated via the production parts cut. Under the high stock removal conditions, the 10.3 MPa coolant pressure setup increased tool life by about 100%. Based on this result, it was concluded that the large part hard-turn feature could be completed within the extended tool life (no tool failure during the test cut), and productivity could be expected to increase by 46%.

2. Experiment setups

2.1. Setup and data measurement equipment

From production consideration, machining experiments were carried out on through-hardened 52100 bearing-grade steel. Carburized hardened C8620 steel was also selected for the tool life comparison. The steels’ main chemical compositions are shown in Table 1. The 52100 steel’s hardness was heat-treated to the range of 58–62 HRC. The C8620 steel was carburized and hardened to the same surface hardness, with a hardened layer thickness of 1.5 mm to 3.0 mm. The sample workpiece was made from a part with an OD of 400 mm and an available cutting length of 50 mm. The tests were conducted with a high-precision CNC vertical lathe using a magnetic chuck to hold the workpiece on the face. All the test cuts were carried out on the OD straight surface.
Table 1. Chemical composition of test steels.

| Harden steel | C %      | Mn %     | Cr %     | Ni %     | Mo %     |
|--------------|----------|----------|----------|----------|----------|
| 52100        | 0.93–1.1 | 0.25–0.45| 1.3–1.6  | 0.14–0.25| 0.04–0.1 |
| C8620        | 0.8–1.0  | 0.7–0.9  | 0.4–0.6  | 0.4–0.7  | 0.15–0.25|

An industrial high-pressure pump with a pressure capability of up to 13.8 MPa and a rated maximum flow rate of 5 L/min was used. Pressures ranging from 8.0 to 10.3 MPa were tested. A Sandvik standard tool holder equipped with a high-pressure coolant jet nozzle applied the coolant. The cutting tool used was a Sumitomo CNGA turning insert with a tool nose radius of 1.2 mm and a CBN tip grade of BNC200. The temperature measurement thermocouple was made from K type resistant wire with a thermal sensing conjunction tip size of about 0.2 mm. The thermocouple was mounted in a ground slot underneath the CBN insert tip. The distance from the tip location to the cutting edge was about 0.8 mm perpendicular to the flank face. The output temperature analog signal from the thermocouple was acquired by a Yokogawa DL750 digital waveform recorder with a built-in thermal voltage signal amplifier module. The coolant used in the experiments was water-based. Figure 1 shows the experimental machine, tooling, thermocouple mounting location and high-pressure coolant setup.

Figure 1. High-pressure coolant hard turning experiment setup: (a) high-pressure coolant connection to the tool, (b) thermocouple installation location, (c) coolant ejection status.

2.2. Experiment procedures

The hard-turning experiments were conducted with the following conventional low pressure and high-pressure coolant parameters.

- The first set of experiments was conducted to cut material and measure the temperature difference between the conventional (0.4 MPa) and high-pressure coolant conditions. The purpose of this test was to validate that the high-pressure coolant reduced cutting temperatures and to identify what effect it had on hard-turning the 52100 steel.
- The second set of experiments was conducted with the conventional low-pressure coolant applied at a higher material removal rate cutting to identify the tool failure mode under high material removal rate cutting conditions.
- The third set of experiments compared the tool life improvement results under the high-pressure coolant and validated the high-pressure coolant as the key factor in affecting cooling and lubrication capability and thereby improving tool life.
- The final test used the highest removal rate parameters identified in the previous tests and production parts to validate the feasibility of successfully finishing the production cut and assessing whether productivity had been enhanced.
3. Results of experiments and discussion

3.1. Temperature under the conventional and high-pressure coolant conditions

All the temperature data collected from the experiments under different cutting conditions are shown in Figure 2. Figure 2(a) shows the cutting temperature measured during hard turning using lower stock removal with the conventional coolant pressure (0.4 MPa) applied. The highest temperature was about 130 Celsius degrees at the measurement location, which was 0.8 mm underneath of the insert tip rake face. Although this was not the direct cutting point surface temperature, it was proportional to it, enabling the quantitative evaluation of the rake face temperatures under the different turning process conditions. Figures 2(b), (c) and (d) present the turning temperatures at high stock removal rates with conventional coolant and high-pressure coolant supply conditions.

Figure 2. Temperature comparisons of high-pressure (10.3 MPa) coolant vs. conventional (0.4 MPa) coolant during hard turning at different process cutting conditions.

All above results clearly indicated that the high-pressure coolant application would have much lower cutting-induced temperatures than the conventional-pressure coolant application. The applied high-pressure coolant tests demonstrated significant cutting zone temperature reduction capability which gave the potential for the tool life to increase in high stock removal cutting.

The relationship of temperatures and material removal rates were further analyzed for each setup of conventional pressure coolant conditions. As shown in Figure 3, the increases in cutting speed, feed rate and depth of cut would increase the cutting material removal rate, however, the insert rake face temperature also increased, it shows the cutting speed has the most significant impact on the temperature change in the above three cutting parameter conditions. Further examination of this data shows that at a fixed cutting depth Doc of 0.1 mm and feed of 0.1 mm/rev, as in Figure 3(a), the ratio of temperature increase to material removal increase since speed change is about 0.15°C/mm³ (calculated from the data (170°C-125°C)/(1700mm³-1400mm³)). From figures 3(b) and (c), these ratios are 0.013°C/mm³ and 0.011°C/mm³, respectively. These results demonstrate that the temperature in the cutting zone is more sensitive to cutting speed than to the other two primary process parameters. So, from the process optimization point of view, with cooling condition fixed, the selection of a larger cutting depth or faster feed rate is the most effective strategy to achieve less tool wear by temperature reduction and in turn to gain economical productivity enhancement.

Figure 3. Hard turn material removal rate vs. average temperature increase under different setup conditions at low pressure coolant cutting application.
3.2. High stock removal hard turning with conventional coolant pressure and tool failure mode

Figure 4 shows images of insert wear and failure status on the rake and flank faces after the high stock material removal hard turning experiment in which the conventional-pressure (0.4 MPa) coolant was applied.

In Figure 4(a), the cutting tool crater wear is very severe. The flank wear, however, appears to follow a normal pattern. As Figure 4(b) shows, its maximum flank wear land VB was less than 0.2 mm [7-8]. From the rough turning point of view, this amount of flank wear would be negligible. Although there was severe crater wear on the rake face, the insert cutting time was short, only 12 minutes, a much shorter length of time than normal production hard turning on the 52100 hardened steel case.

![Figure 4](image_url)

**Figure 4.** Tool wear after 12 minutes of hard turning at high stock material removal rate with conventional-pressure (0.4 MPa) coolant supply. (a) is crater wear at 12 minutes cut time, (b) is the flank wear and the (c) is the fracture happened between 12-16 minutes cutting time.

In the test after the tool wear was measured, the insert was put back for continued cutting, but the test could not be completed, the insert fractured between the 12 minutes to 16 minutes portion of the test cycle as Figure 4(c) shows, it can be observed that the insert edge fractured from the highest-temperature point at the cutting edge lead-in side, which is also the maximum crater wear location. From this significant rake face wear/fracture characteristics, it can be concluded that under the high stock material removal cutting condition, tool damage is due primarily to rapid rake face crater wear and sudden transition to cutting-edge fracture.

To further understand what failure mode caused the insert to suddenly fracture, a crater wear test was conducted numerous times at a relatively lower cutting speed (100 m/min instead of 150 m/min), utilizing the high material removal rate cutting condition setup. This time, the insert was observed under a high-magnification microscope at four-minute check intervals in the test cycle. As shown in Figure 5, one deep micro crack and material spalling spot was observed in the crater area, which initiated from the highest-temperature spot after the insert had been in use for 24 minutes of cutting.

![Figure 5](image_url)

**Figure 5.** Tool wear after 24 minutes of hard turning at high stock material removal rate with conventional-pressure (0.4 Mpa) coolant supply.
It could be assumed that during cutting, the insert rake face experienced mechanical abrasive wear and, simultaneously, a thermal chemical oxidization reaction occurred on the tool rake face. Figure 6 is an SEM photo of an insert crater wear spot on the rake face after hard turning. The black dots are CBN grains and the gray area is bonding material. An EDS analysis was performed at spot 1 and 2 locations (one CBN grain and one bonding spot). The EDS analysis results indicated that high oxygen content was detected in the spot 2 location. In almost all cases, the metal oxidation structure was brittle and weaker in strength than the initial bonding metal [9].

Figure 6. Chemical components found in crater wear area via EDS analysis.

The spot 1 location possessed a relatively higher concentration of boron elements and a much lower oxygen component. The spot 1 and 2 comparison indicated the insert bonding metal material had undergone a strong chemical oxidization reaction under high temperature. This oxidization reaction directly weakened the tool bonding material strength and was then wiped away by the flowing chip. The insert rake face wear process was accelerated by the hard carbide particles in the hardened 52100 steel chips. Figure 7 shows a typical used insert wear pattern after hard turning. Its surface appears to have an asperity layer that was formed by the CBN grains and oxidization of the bonding metal, with some adhesive steel buildup from the workpiece.

When the crater wear on the cutting edge became deep enough, an area of thermal stress concentration developed. When this concentrated stress exceeded the surrounding bond metal’s strength limit, it generated a thermal crack. As the experimental cutting and wear continued, the cutting edge became more and more weak, and the crack propagated quickly into the neighboring area. Impelled by the thermal and cutting force impact, the crack extension finally induced the bulk bonding metal to fracture. In other words, insert failure was dependent on how fast the crater wear developed.

3.3. Cooling capability and tool life improvement after application of high-pressure coolant

The above description of the benchmarked (conventional coolant pressure) tool failure mode shows that improvement in tool fracture/failure performance in high stock removal conditions with conventional coolant pressure could be achieved except for improving the strength of insert material’s thermal mechanical performance, which is most insert manufacturers’ current development priority. Using high-pressure coolant to accelerate the reduction of heat created in the cutting zone is an effective alternative method.
The images in Figure 8 compare the chip thermal effect and size breakage capability of hard turning experiments on the 52100 through-hardened steel.

**Figure 8.** Chip formation comparison under conventional and high-pressure coolant conditions.

The chips formed in Figure 8(a) under the conventional coolant pressure condition have a long strap shape. Since the contact length between the chip back face and insert rake face is longer, as the heat generation model in Figure 9 shows, this longer contact length creates the potential for more friction and heat to be introduced from the sliding interface area. Conversely, in Figure 8(b), all the chips formed under the high-pressure coolant condition are in the shape of short pieces. Further, when comparing the chip colors in Figures 8(a) and (b), one can see a clear difference: Under the conventional coolant condition, the chips are a dark color, which indicates that the steel experienced a strong oxidation reaction that occurred in the high-temperature environments. But under the high-pressure coolant condition, the chips have retained their original metal color. This characteristic coloration indicates that the high-pressure coolant reduced the high-temperature chemical oxidation reaction in the cutting zone not just by reducing the chip and insert rake face contact length, but also by producing a hydrodynamic lift effect that further reduced contact friction and carried away more heat from the shear plane.

**Figure 9.** Heat source model of turning process. The main heat is from material shearing, chip back face’s touch creating scratch friction effect in the material removal process.

Figure 10 is a tool crater wear evolution comparison of high stock material removal hard turning under the different coolant pressure application conditions. The comparison images clearly demonstrate that in the high-pressure coolant case, it takes nearly twice as long before tool crater wear developed as it does in the conventional low-pressure coolant case (54 minutes vs. 27 minutes). Longer tool life means larger dimension parts for which the hard-turning process can be carried out with no tool
fractured. In production the tool life should be long enough to finish at least one single cycle pass with no mid-cycle tool change. It should be noted that to meet the one complete pass tool life restriction in production practice the material removal rate (lower feed, depth of cut, etc.) must be sacrificed to achieve longer tool life.

Figure 10. Tool crater wear evolution comparison at cutting conditions: speed 100 m/min, feed 0.2 mm/rev, and DOC 1.0 mm.

3.4. Cutting speed and material effect on the hard turn machinability under high pressure coolant condition

In the previous temperature tests, it was demonstrated that the higher the material removal rate, the higher the cutting temperature will be. The temperature increase is most sensitive to the cutting speed. The next set of experiments was performed to validate that this principle applies to tool wear either in the lower or high-pressure coolant condition.

The images in Figure 11 show the results of tool wear experiments using different cutting speeds. It is clearly indicated that even under the high-pressure coolant condition, tool crater wear is still very sensitive to cutting speed. These results are consistent with the measured temperature test results. With regards to tool life, it can also be seen that increasing material removal rate by increasing speed is the last option for process optimization.

Figure 11. Comparison of cutting speed effect on tool crater wear under high pressure coolant condition.

The images in Figure 12(a)(b)(c)(d) are of carburized C8620 hardened steel tested under the high stock removal rate and high-pressure coolant conditions and comparison with through harden steel 52100. The images indicate that when same cutting parameters are set up with regard to cutting time, faster feed and larger depth of cut, the carburized steel manifests much less tool crater wear. The authors thought except the high pressure coolant effect since carburized steel has less hard carbide particle scratch effect that benefits the tool wear reduction. It is almost four times less when crater area is used as the evaluation criteria.
3.5. Workpiece material microstructure change under high pressure coolant condition

In Figure 13, it could be seen how material surface microstructure is affected after high stock removal hard turning with the high-pressure coolant. On the top of the machined surface, a mechanical hardened layer on the order of 1–2 μm can be seen. Judging by the color under this layer, no further thermal damage has occurred. If the layer had undergone thermal damage, it would be in the tempered black color. Since the high stock removal process is used for rough and semi-finishing, even if a thin mechanical hardened surface layer develops, it would be removed by the finishing step, which is normally set up at depth of cut of 100 μm.

Figure 13. Surface microstructure under high stock removal and high-pressure coolant conditions.

4. Large diameter part validation cut and productivity enhancement estimation

As shown in Figure 14 machined part, one 52100 hardened steel part was selected to conduct the validation cut at the high stock removal rate (30,000 mm³/min setup) with surface speed 100 m/min, feed rate 0.25 mm/rev, DOC 1.2 mm, and the high-pressure 10.3MPa coolant applied. Figure 14 not only shows that the cutting was completed successfully, but also clearly shows that the high-pressure coolant has very good chip control capability. Figure 14 showed validation cut is the new insert edge test case, no big chips remain on the chuck table, all the cut chips are very small and can easily be flooded away by the high pressure flushing coolant, only a few of them are held by the magnetic poles on the chuck table.

Another large part with 1.92 meter diameters was selected for the case study to estimate the productivity gains that could be achieved in practice with this method of high stock removal hard turning. The OD and ID hard turned surfaces were about 72 mm and 260mm long, Table 2 provides a comparison of the cycle time reduction if the high-pressure coolant is used in the process instead of the conventional low-pressure (0.4 MPa) coolant. Since it was feasible for this setup to apply the 30,000 mm³/min material removal rate, the hard turn time was cut down from the initial 320 minutes to 171 minutes, which corresponds to a 46.5% cycle time savings in the process. This cycle time reduction represents a significant increase in productivity.
### Table 2. Large cutting surface part cycle comparison

| HT features | Current LP & speed 182 m/min | Enhanced HP & speed 100 m/min |
|-------------|------------------------------|------------------------------|
|              | HT (mm) | Doc (mm) | Feed (mm/rev) | Pass | HT time (min) | Doc (mm) | Feed (mm/rev) | Pass | HT time (min) |
| OD          | 3.2      | 0.6       | 0.15           | 6    | 96           | 1.2      | 0.25           | 3    | 51           |
| ID          | 2.4      | 0.6       | 0.15           | 4    | 224          | 1.2      | 0.25           | 2    | 120          |
| **Total cutting time** | **320** |           |                |      |              | **171** |                |      |              |

5. Conclusions

High-pressure coolant-applied high stock removal hard turning was tested in through-hardened 52100 and carburized hardened steel under different production parameters. The tool failure mode and proposed improvement approach were investigated with the goal of making the process feasible for large size product hard turning. Preventing the fast crater wear on the tool cutting edge was proved to be the key control factor. The following conclusions can be drawn from this investigation:

- Under high stock removal conditions, the quick tool failure is primarily due to the severe crater wear making the insert cutting edge weaker; at some point a thermal crack is induced, followed by sudden chipping and fractured out.
- In addition to removing more heat from the cutting zone, the high-pressure coolant jet enhances lubrication by creating a hydrodynamic fluid layer effect between the back face of the chip and the front of the tool rake face. It also breaks the long, continuous chips down to small, non-continuous pieces, which reduces the chip contact length in the tool rake face and consequently reduces friction/heat diffusion into the tool.
- With this enhanced cutting zone temperature reduction capability, tool life under the high stock removal condition could improve 100% in rough hard turning.
- The carburized hardened steel also has shown much better tool life under the high stock removal hard turning case since this material has less hard carbide particle scratch effect.
- The larger part production application case study indicates that productivity can be expected to increase by 46% when the high-pressure coolant is applied.

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