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An Investigation on Chip Morphology of Hardened Steel (52 HRC) During Hard Turning

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Abstract

In this study, the variation in chip morphology was investigated with changes in coolant use (Dry & Flooded) and different cutting parameters (cutting speed, feed rate, and depth of cut). The study involved cutting D2SKD steel, which had been heat treated to a hardness of 52 HRC, with coated carbide inserts in two different machining conditions. Both the cutting fluid and the hardness of the material were kept constant. The number and combination of distinct cutting parameters were determined using the Design of Experiment (DOE). The results of this study demonstrate that feed rate, cutting speed, depth of cut and machining environment each has distinct effects on chip morphology, with feed rate and speed possess the most significant influence.

Keywords: Hard turning, Surface roughness, Design of experiment, Analysis of variance

1. Introduction

Chip morphology significantly influences the performance of machining processes, especially in hard turning of high-strength materials like hardened steels. As the demand for high-dimensional accuracy and surface integrity grows, understanding the underlying mechanisms of chip formation becomes crucial for optimizing cutting conditions and improving overall machining efficiency. Hard turning, involving materials with hardness levels between 45 and 70 HRC, has become a viable alternative to grinding due to advancements in cutting tool materials like cubic boron nitride (CBN) and improved machine tool stability. However, challenges persist, particularly in chip management, surface degradation, and tool wear, all of which are influenced by cutting parameters such as speed, feed rate, depth of cut, and the machining environment .

Recent research has highlighted the complex nature of chip formation in hard turning under varying cutting conditions. Chip management is also an open issue that needs further investigation [1]. Continuous chips tend to form at lower cutting speeds, resulting in smoother surfaces but presenting challenges related to chip control [3]. As cutting speed increases, chip morphology transitions to serrated or segmented chips due to localized shear banding and increased strain rates, which can degrade surface quality and accelerate tool wear [4]. Cutting edge rounding further increases stresses at the tool-workpiece interface, exacerbating chip segmentation [2]. For example, at cutting speeds up to 5200 m/min, continuous chips are still generated, leading to surface degradation due to material buildup and inefficient chip evacuation [1]. The transition from continuous to segmented chips directly impacts surface quality, with serrated or sawtooth chips causing surface defects and tool wear [6]. Studies on various materials, such as EN X160CrMoV12 steel, have shown that cutting conditions significantly affect chip formation, with cutting forces decreasing at higher speeds [7]. Recent advancements in turning processes, including the use of CNC machines and coated tools, have enhanced quality and tool life, while research continues to focus on optimizing these coatings for hard materials and exploring eco-friendly lubrication methods [8]. However, limited research has focused on machining of high-carbon steels, such as 52 HRC hardened D2SKD steel, using advanced cutting tools like CBN under different environmental conditions. Moreover, few studies have examined the effects of machining environments, particularly flooded cooling, on chip morphology and surface integrity.

The objective of this study is to investigate the effects of cutting parameters—cutting speed, feed rate, and depth of cut—on chip morphology during the hard turning of D2SKD steel under both dry and flooded conditions.

By analyzing chip morphology and surface roughness, this research aims to establish functional relationships between cutting parameters and the resulting chip characteristics. Taguchi's DOE and ANOVA will be employed to quantify these effects, contributing to the optimization of hard turning processes for high-carbon hardened steels, which have yet to be extensively studied, particularly with the use of CBN tools under flooded environments.

2. Experimental procedure and materials used

For the experiment, D2SKD steel was selected as the workpiece. The workpiece was a cylindrical bar (length = 400 mm and diameter = 60 mm). The chemical properties of the workpiece material and specification of the CBN insert are given below in Tables 1 and 2, respectively. Initially, the hardness of the material was 20-22 HRC before turning operation. Then the hardness of the material was raised by 52±2 HRC, which had been conducted at the heat treatment lab of the Bangladesh Industrial and Technical Assistance Center (BITAC).

Table 1. Chemical composition of D2SKD steel.

Elements	Volumetric Percentage
C	1.40-1.60
Si	0.10-0.60
Mn	0.20-0.06
Cr	11.0-13.0
Mo	0.70-1.00
V	0.70-1.00

Table 2. Tool Insert specifications

Nomenclature	Type
Insert	Coated carbide inserts SNMG120408)
Co held	PSBNR2525M12
Coating	TiCN & WC
Back rake angle	-6º
Side rake angle	-6º
End relief angle	6º
Side relief angle	6º
End cutting edge angle	15º
Side cutting edge angle	75º
Nose Radius	0.8 mm

The hardening process involves heating the components over the critical (normalizing) temperature, sustaining this temperature for one hour per inch of thickness, and subsequently quenching the material to facilitate its transformation into a significantly harder, stronger structure. The workpiece was preheated to 500°C to decrease the possibility of cracking. The workpiece was then heated to a temperature range of 950–1000 °C for a duration of 8–9 hours. Subsequently, the material was subjected to air cooling. Oil cooling wasn't utilized to achieve the necessary hardness. We are utilizing high-carbon steel, which may exceed the intended hardness if subjected to oil cooling. Consequently, to achieve the requisite hardness, the material was air-cooled instead of oil-quenched. At the end of the operation, the hardness was greater than 55 HRC. The workpiece was thereafter treated to avoid cracking and reduce hardness. The material was tempered for six hours at a temperature of 500 to 550 °C. Five hardness readings were collected along the surface at the end of the tempering, and the average hardness of the workpiece was 52±2 HRC. Then the machining operation has been done.

In order to systematically collect the corresponding responses, a DOE technique was applied to generate a matrix containing every feasible combination of machining conditions. The study is based on three quantitative 3-levels and one qualitative 2-levels factors. The factors levels are shown in Table 3.

Table 3. Attribution of the levels of factor.

Cutting Parameters	Level 1	Level 2	Level 3
Cutting Speed, v (mm/min)	68	96	136
Feed Rate, f (mm/rev)	0.10	0.14	0.20
Depth of Cut, d (mm)	0.1	0.2	0.4
Machining Condition	Dry	Wet	

Cutting parameters such as cutting speed, feed rate, and depth of cut have been changed during the experiment. The experiment was conducted out in both dry and flooded environments, with the chips being collected after each run. Before beginning the experiment to skin out the outer surface, a rough incision of 0.2 mm was made. The experiment was then carried out, with the value of surface roughness for each run being measured. Chips from each run were also collected to investigate how the cutting parameters affected the chip shapes and colors. 18 sets of machining conditions and results, as shown in Table 4:

Table 4. Machining conditions from L18 orthogonal array with chip thickness ratio

Run	Cutting Parameters			Condition	Chip Thickness Ratio (T1/T2)
	Cutting Speed (mm/min)	Feed Rate (mm/rev)	Depth of Cut (mm)		
1	68.03	0.100	0.1	DRY	0.41
2	68.03	0.136	0.2	DRY	0.37
3	68.03	0.200	0.4	DRY	0.90
4	95.82	0.100	0.1	DRY	0.38
5	95.82	0.136	0.2	DRY	0.75
6	95.82	0.200	0.4	DRY	0.69
7	136.06	0.100	0.2	DRY	0.68
8	136.06	0.136	0.4	DRY	0.88
9	136.06	0.200	0.1	DRY	0.27
10	68.03	0.100	0.4	WET	0.96
11	68.03	0.136	0.1	WET	0.16
12	68.03	0.200	0.2	WET	0.55
13	95.82	0.100	0.2	WET	0.63
14	95.82	0.136	0.4	WET	**1.04**
15	95.82	0.200	0.1	WET	0.33
16	136.06	0.100	0.4	WET	**1.03**
17	136.06	0.136	0.1	WET	0.45
18	136.06	0.200	0.2	WET	0.55

3. Results and Discussion

An optical microscope was used to examine the chip morphology in matrix form, revealing a secondary

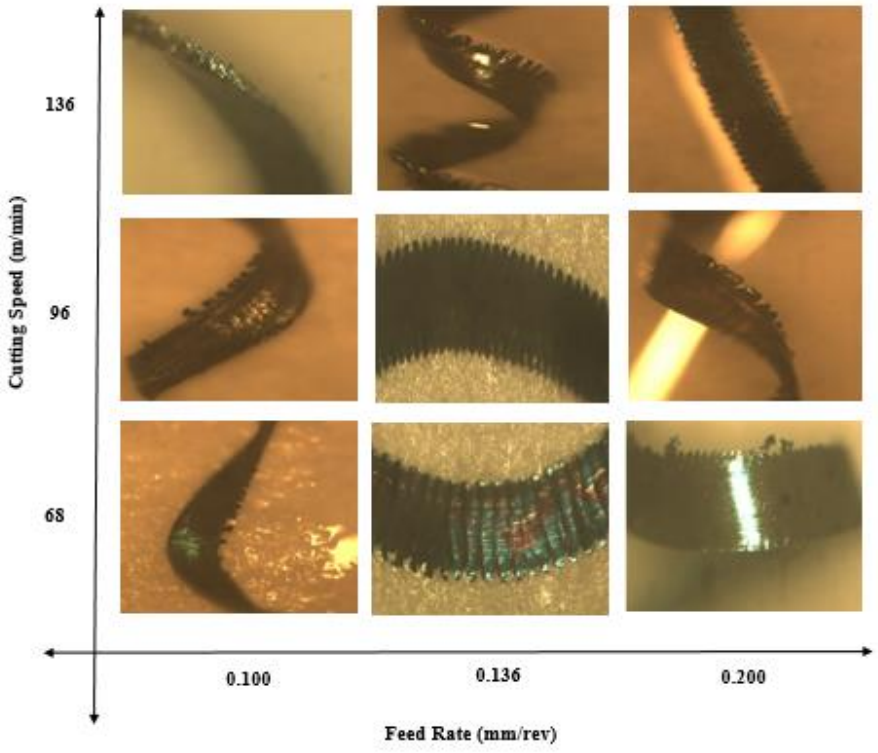


Fig. 1. Microscopic chip morphology for dry machining conditions

deformation zone at the tool chip contact. For the various cutting combinations of dry condition selected, microscopic pictures of the chips at Fig. 1 indicate localized material deformation with fractures in the three directions (cutting, feed, and push), but no full chip fracture. The chips have a saw tooth pattern, which can be seen clearly in a microscopic representation in the axial plane, which corresponds to the feed force (free surface).The distance between two succeeding segments increases as the feed rate increases. Finally, best quality of surface roughness comes from the highest speed (136 rpm) and lowest feed (0.100 mm/rev).

In case of wet condition Fig. 2: A small number of chips has a saw tooth pattern; this may occur due to the tool wear during machining (as dry-conditioned runs had been performed first) and also due to the flooded condition, the chip's tooth broke. This is another reason why the surface roughness of the flooded condition is a bit higher than the dry condition. During the cutting operation, the tooth grazes the machined surface.

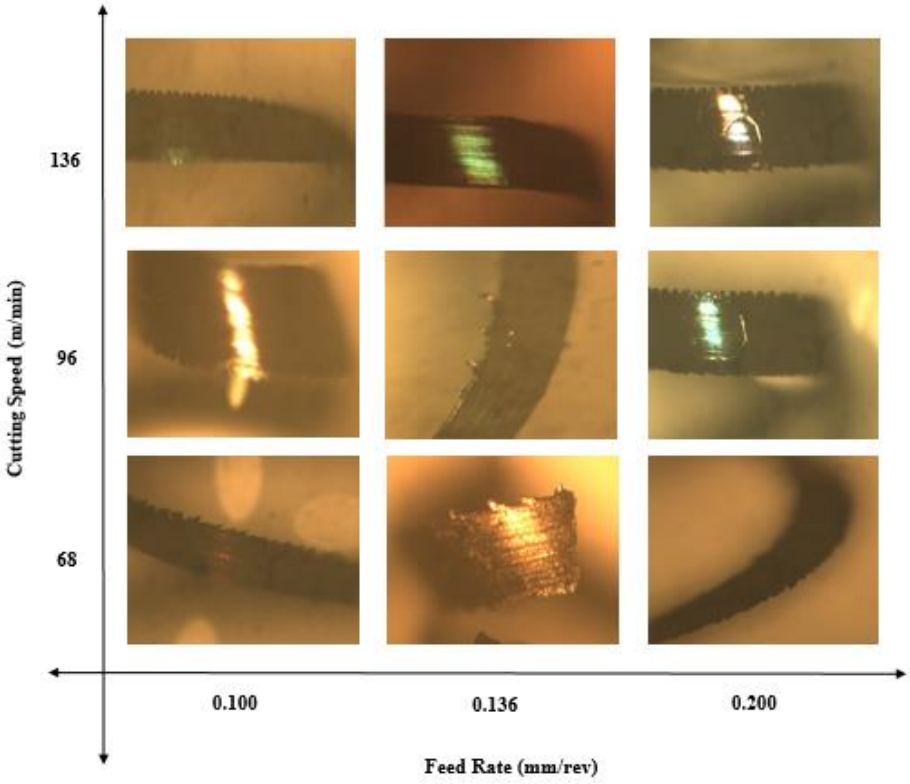


Fig. 1. Microscopic chip morphology for wet machining conditions

Figs. 3 and 4 showed that, at low cutting speeds, continuous chips tend to form, resulting in smoother surfaces but presenting chip control challenges. As cutting speed increases, chip morphology transitions from continuous to serrated or segmented due to localized shear banding and increased strain rates [13, 14]. This transition occurs when strain rate hardening dominates over temperature softening [5, 11], generally accompanied by decreasing cutting forces [12]. Feed rate also plays a crucial role; lower feed rates produce thinner chips and better surface finish, whereas higher feed rates lead to thicker chips and increased segmentation. The interaction between these parameters is complex; high speeds and low feeds tend to produce more segmented, thinner chips, while low speeds and high feeds result in thicker, more continuous chips.

At lower cutting speeds, continuous chips are common. These chips are long and ribbon-like, and they can sometimes cause handling difficulties due to tangling. Chips with a bright silver or shiny appearance were detected at lower cutting speeds. As cutting speed increases, chips often convert to serrated or segmented forms, and chips often take on colors ranging from straw-yellow to deep blue, which coincides with the rising temperature in the cutting zone. Blue/Burn blue chips have been spotted under high speed and high feed rate. These colors indicate excessive heat, which can significantly damage both the tool's lifespan and the workpiece's surface integrity owing to thermal deterioration. In hard turning, continuous chips are less common, but when they emerge, they can suggest smooth cutting without excessive segmentation.

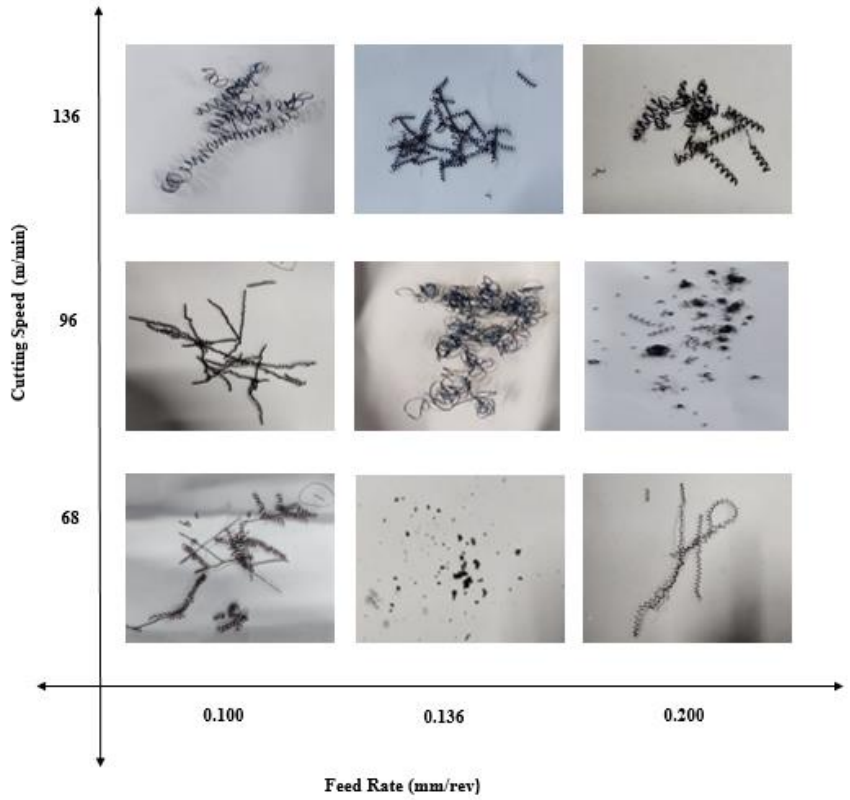


Fig. 3. Chip shape for the dry machining condition

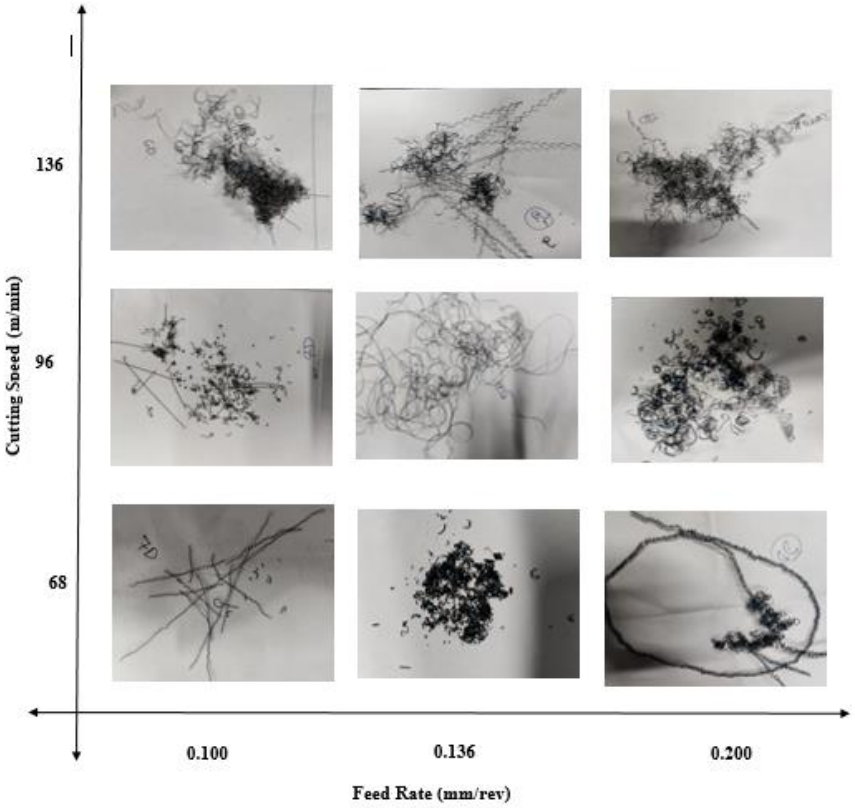


Fig. 4. Chip shape for wet machining condition

4. Conclusion

In hard turning, where workpiece hardness typically varies from 45-70 HRC, material qualities strongly influence chip formation, with harder materials yielding more segmented chips due to lower plasticity. These features of chip formation affect important machining outcomes, including surface quality, tool wear, and the necessity for effective chip breaking procedures. To achieve the appropriate chip morphology, surface finish, and tool life in hard turning operations, it is necessary to optimize the balance between cutting speed and feed rate.

5. References

[1] Kishawy, H. A., Dumitrescu, M., Ng, E. G., & Elbestawi, M. A. (2005). Effect of coolant strategy on tool performance, chip morphology and surface quality during high-speed machining of A356 aluminum alloy. International Journal of Machine Tools and Manufacture, 45(2), 219-227.
[2] Andrés Iglesias, G. (2023). Experimental analysis of chip formation when hard machining as a function of the shape of the cutting edge.
[3] Sobiyi, K., & Sigalas, I. (2015). Chip formation characterisation and Tem investigation of worn PcBN tool during hard turning. Machining Science and Technology, 19(3), 479-498.
[4] Tang, L., Yin, J., Sun, Y., Shen, H., & Gao, C. (2017). Chip formation mechanism in dry hard high-speed orthogonal turning of hardened AISI D2 tool steel with different hardness levels. The International Journal of Advanced Manufacturing Technology, 93, 2341-2356.
[5] Wan, L., Wang, D., & Gao, Y. (2016). The investigation of mechanism of serrated chip formation under different cutting speeds. The International Journal of Advanced Manufacturing Technology, 82, 951-959.
[6] Rastorguev, D., & Sevastyanov, A. (2019). Diagnostics of chip formation and surface quality by parameters of the main drive current in the hard turning. Materials Today: Proceedings, 19, 1845-1851.
[7] Mhamdi, M. B., Salem, S. B., Boujelbene, M., & Bayraktar, E. (2013). Experimental study of the chip morphology in turning hardened AISI D2 steel. Journal of Mechanical Science and Technology, 27, 3451-3461.
[8] Sousa, V. F., & Silva, F. J. (2020). Recent advances in turning processes using coated tools—A comprehensive review. Metals, 10(2), 170.
[9] Pusavec, F., Kramar, D., Krajnik, P., & Kopac, J. (2010). Transitioning to sustainable production–part II: evaluation of sustainable machining technologies. Journal of Cleaner Production, 18(12), 1211-1221.
[10] Gajrani, K. K. (2020). Assessment of cryo-MQL environment for machining of Ti-6Al-4V. Journal of Manufacturing Processes, 60, 494-502.
[11Özel, T., & Karpat, Y. (2005). Predictive modeling of surface roughness and tool wear in hard turning using regression and neural networks. International journal of machine tools and manufacture, 45(4-5), 467-479.
[12] Aouici, H., Yallese, M. A., Chaoui, K., Mabrouki, T., & Rigal, J. F. (2012). Analysis of surface roughness and cutting force components in hard turning with CBN tool: Prediction model and cutting conditions optimization. Measurement, 45(3), 344-353.
[13] Salem, S. B., Bayraktar, E., Boujelbene, M., & Katundi, D. (2012). Effect of cutting parameters on chip formation in orthogonal cutting. Journal of Achievements in Materials and manufacturing Engineering, 50(1), 7-17.
[14] Ekinović, S., Begović, E., Fakić, B., Burić, A., & Čeliković, A. (2014). Cold air dry machining Part 2: SEM and Metallographic analysis of the chip. Journal of Trends in the Development of Machinery and Associated Technology, 18(1), 43-46.