Influence of Cutting Process Parameters on Chip Formation with CNMG120408-E-SC3 Inserts

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Abstract: -

Hard machining is a process increasingly endorsed in the manufacturing sector as a substitute for grinding and for production purposes. The critical technological parameters that govern this process include tool wear, machined surface roughness, cutting force, chip morphology, residual stresses etc. This study attempts to analyze the morphology and characteristics of chips produced during the hard turning of hardened alloy steel. The experiments were conducted using RSM Box Behnken Design. The range of each parameter i.e. cutting speed, feed and depth of cut is set at different levels for the analysis purpose. Macroscopic results of chip morphology were correlated with cutting process parameters. The results were evaluated and it indicated that the interaction of process parameters has a significant effect on the control of chip formation. The color of the chips changes from metallic to blue when the cutting speed increases due to heat generated at the tool-workpiece interface and carried away by the chips.

***Keywords**: Alloy steel, Hard turning, Chip formation, Process parameters.*

1. Introduction

Hardened alloy steel, such as EN19, is known for being difficult to cut. To enhance flexibility and facilitate the manufacturing of complex geometries, hard turning was developed, which eliminates the need for grinding operations. EN19 is highly regarded in the industry due to its excellent wear-resistance properties.

The machining of hardened materials has become a highly demanded manufacturing process because of its significant technological and ecological benefits. This development suggests the need for ongoing research to improve quality and control production costs.

2. Literature Review

When evaluating machine attributes related to metal cutting, chip morphology is a critical factor [1]. The formation of chips reveals the fundamental mechanisms involved in the cutting process and the interaction between the workpiece and tool in the cutting zone [2]. Chip morphology is influenced by various cutting parameters, including feed rate, cutting speed, nose radius, and depth of cut [3], as well as thermal behavior during machining and friction between the tool's rake face and the deformed chips [4]. This is important because the heat generated during the cutting process is primarily dissipated through the chip, helping to prevent thermal expansion of the workpiece (Khamen et al., 2007).

According to Kaldor et al. (1979) [5], there are two types of chip forms: 1) acceptable chips and 2) unacceptable chips, categorized by their ease of handling. Acceptable chips do not interfere with the workpiece or tools and do not create disposal issues. In contrast, unacceptable chips disrupt regular manufacturing operations because they tend to tangle around the tool and workpiece, posing safety hazards for operators. These chips can also lead to inconsistent surface finishes and increased tool wear.

Thus, the control of the chip formation mechanism at both micro and macro levels is a possible means to improve machinability [6]. At the macro level, chip formation and flow is due the given cutting conditions and subject to chip curling [7], chip flow angle [8] and chip curve radius [2]. As a result, various shapes of chip can be formed, such as helical, tubular, ribbon, spiral, segmented and snarled [9], [10]. Studying chip formation, its morphology, and the parameters that influence will help us to understand the material removal phenomenon and surface integrity (Ben Salem et al., 2012), as well as the performance of cutting tools (Kumar et al., 2017).

The impact of cutting conditions on chip curling has garnered significant attention. Research indicates that increasing the feed rate and the depth of cut leads to greater chip curling [11].

Fang [7] investigated on chip control and found that higher cutting speeds combined with lower feed rates can help prevent chip curling, whereas increasing chip thickness contributes to more curling.

Numerous studies have examined the chip flow angle, revealing that tool geometry, feed rate, and depth of cut greatly influence the chip flow angle [12] [13]. Research has shown that the chip curve radius is one of the most significant factors affecting chip breaking. A smaller chip radius increases the likelihood of breakage due to the bending moment involved. When the chip curvature is smaller, the difference between tension and compression stresses is amplified, resulting in increased strains that can lead to fracture [14].

Chip breaking during the cutting process can be classified into two types: natural and forced. Natural chip breaking occurs when the chip breaks on its own without contacting any obstacle, while forced chip breaking happens when the chip comes into contact with the tool or workpiece [9].

Ekinović et al. (2014) [15] found that the use of dry machining technology on 30CrNiMo8 steel can significantly influence chip morphology. Khorasani et al. (2012) noted a degradation in surface quality resulting from the generation of fragmented chip segments during hard machining.

Sahoo et al. (2012) [16] found that the color of the chip serves as an indicator during the cutting process. Elshwain et al. (2020) [17] confirmed that the characteristics of chip morphology change when the cutting speed and feed rates are adjusted during the hard turning of stainless steel. Specifically, increasing the cutting speed from 100 to 170 m/min transforms the chip type from a twisted long ribbon to a snarled tubular shape.

Palanikumar et al. (2023) [18] investigated the impact of cutting conditions on cutting zone temperature when machining Ti-6Al-4V, using PVD carbide and CVD-coated tools. Their results demonstrated that cutting temperature increases with cutting speed, and CVD-coated tools produce shorter chips compared to PVD-coated tools.

Leadebal et al. (2019) [19] studied the effects of hard turning on a hardened AISI D6 tool steel bar using both dry and cryogenic machining conditions. In the cryogenic machining process, liquid nitrogen was applied to the flank face, rake face, and both faces of the PCBN inserts. The cutting parameters—such as cutting speed, feed rate, and depth of cut—were kept constant throughout the machining process. The study focused on tool wear and chip morphology as the main output variables. The results showed that the use of liquid nitrogen significantly reduced tool wear, leading to a 50% longer tool life compared to the dry machining process. Additionally, the occurrence of chip segmentation was lower under cryogenic conditions compared to the dry method.

Rath et al. (2019) [20]collected chip samples after each experiment, measuring the thickness of each sample using a digital caliper. They documented the chips' color, shape, thickness, and chip reduction coefficient. The results indicated that the color of the chips changed from metallic to burn blue as the feed rate and cutting speed increased. The burn blue hue signifies a significant increase in heat generated at the interfaces between the tool and the workpiece. At higher axial feed rates and depths of cut, helical saw-tooth types with non-uniform segmented chips were observed due to increased friction on the rake surface.

Discontinuous chips were produced at slower cutting speeds, while serrated chips occurred at faster cutting speeds. The chip reduction coefficient is directly proportional to the thickness of the chip. As the depth of cut and cutting speed increase, the chip reduction coefficient decreases. The lower surface of the machined chip appears smoother with prolonged scratch marks, resulting from lower friction and favorable wear mechanisms. In contrast, the upper surface continuously deforms, creating a rough surface characterized by intense wrinkles.

Demirpolat et al. (2023) [21] examined the macromorphology of chips to understand the influence of cutting conditions. They found that using a dry turning method at both low and high cutting speeds produced chips with a long, tubular, and snarled shape. The thickness of the chips slightly decreased as the cutting speed increased. When the feed rate was adjusted from high to low, tubular and washer-type chips were formed. However, at high cutting speeds and feed rates, the predominant chip type was ribbon-shaped, which then transformed into a tubular, snarled type as the feed rate decreased. The largest chips and roughest surfaces were produced at higher cutting parameters during dry machining. Snarled chips contributed to increased temperatures, leading to poor machining performance in dry-cutting conditions. As the cutting speed and depth of cut increased, the temperature also rose, resulting in tighter and more compact chip forms.

This study focuses on examining the chip morphology resulting from the turning of hardened alloy steel EN 19 using PVD coated carbide inserts with a nose radius of 0.8 mm. The process parameters investigated include cutting speed, feed rate, and depth of cut, along with tool-related parameters such as the nose radius. The primary response variable selected to evaluate machining efficiency and tool performance was chip morphology. The experiments were carried out using the Response Surface Methodology (RSM) with a Box-Behnken Design.

3. Experimental Set Up and Methodology

Workpiece Material

The workpiece material used is hardened alloy steel EN19, with a diameter of 30 mm and a length of 80 mm. This material has been hardened to 55 HRC through a tempering heat treatment process. EN19 is a unique blend of chromium and molybdenum, making it an ideal choice for applications that require high strength, shock resistance, and durability. It is suitable for high-load applications, such as automotive gears and parts, shafts, towing pins, load-bearing tie rods, and various components of machine tools.

Cutting Tool and Tool Geometry

Specification of insert

For the turning of EN19 alloy steel, PVD coated inserts of grade CNMG120408 - E-SC3 from ACHTECH were selected. This grade features a submicron carbide substrate combined with high hardness and a nano-layered PVD coating, enhancing both hardness and oxidation resistance at higher machining speeds. Table 1 indicates the specification of PVD coated CNMG insert.

Table 1: Specifications of PVD coated CNMG insert

Company Code	Grade manufacturer's designation	Inscribed circle diameter	Cutting edge length	Corner radius	Insert thickness	Net weight	Insert Hand
ACHTECH	PVD	12.70 mm	12.9 mm	0.80 mm	4.76 mm	0.009 kg	N – Neutral

Specification of tool holder

The selected insert is of grade CNMG120408 - E-SC3, which was clamped onto tool holder ECLN L 2525 M12.

Machine Tool

The machine tool used in this study is manufactured by the Ace Micromatic Group with model number LT - 20 X. The LT-20 XL machines are powerful turning centers that are suitable for medium-sized components.

Selection of input Factors and their levels

It was found that there are various factors, which directly or indirectly influence the performance of cutting tools in hard turning of hardened EN19 alloy steel with PVD coated insert. In this experiment study, three parameters cutting speed, feed rate, and depth of cut, were selected as input factors. The tool nose radius was taken as 0.8mm. Table no. 2 shows the input factors and their respective levels.

Table 2: Levels of Input Process Parameters

Factors	**Cutting Parameters**	**Unit**	**Levels**		
			1	2	3
Variable	Cutting Speed	r.p.m	1500	1750	2000
	Feed	mu	0.025	0.0725	0.125
	D.O.C.	Mm	0.10	0.15	0.20
Fixed	Tool Nose Radius	mm	0.8		

Design of Experiment

Seventeen experiments were conducted using the Response Surface Methodology (RSM) with a Box-Behnken Design. Table no. 3 shows the RSM design of experiments

Table 3: Design of experiments using RSM (Box-Behnken Design)

S. No.	**Speed**	**Feed**	**DOC**	**S. No.**	**Speed**	**Feed**	**DOC**
1	1500	0.125	0.15	10	1500	0.0725	0.2
2	2000	0.0725	0.1	11	1750	0.0725	0.15
3	1500	0.025	0.15	12	1750	0.125	0.2
4	1750	0.0725	0.15	13	1750	0.0725	0.15
5	1750	0.125	0.1	14	2000	0.125	0.15
6	2000	0.0725	0.2	15	1500	0.725	0.1
7	2000	0.025	0.15	16	1750	0.725	0.1
8	1750	0.0725	0.15	17	1750	0.025	0.2
9	1750	0.0725	0.15				

The primary response variable selected to evaluate machining efficiency and tool performance was chip morphology.

Experimental Procedure

The cylindrical workpiece made of EN19 alloy steel was mounted on a rigid CNC lathe machine. A PVD-coated insert, designated CNMG120408-E-SC3, was secured in the tool holder. The experiments were conducted according to the specified design (refer to Table 3). Prior to starting the first experiment, the workpiece was

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prepared, and a turning length of 60 mm was selected. For each experiment, a new workpiece and insert were utilized.

4. Result and Discussion

This section discusses the experimental results of chips collected after each experiment for the macro analysis while turning hardened alloy steel EN19 with a PVD coated insert. The chips were classified according to ISO standard 3685.

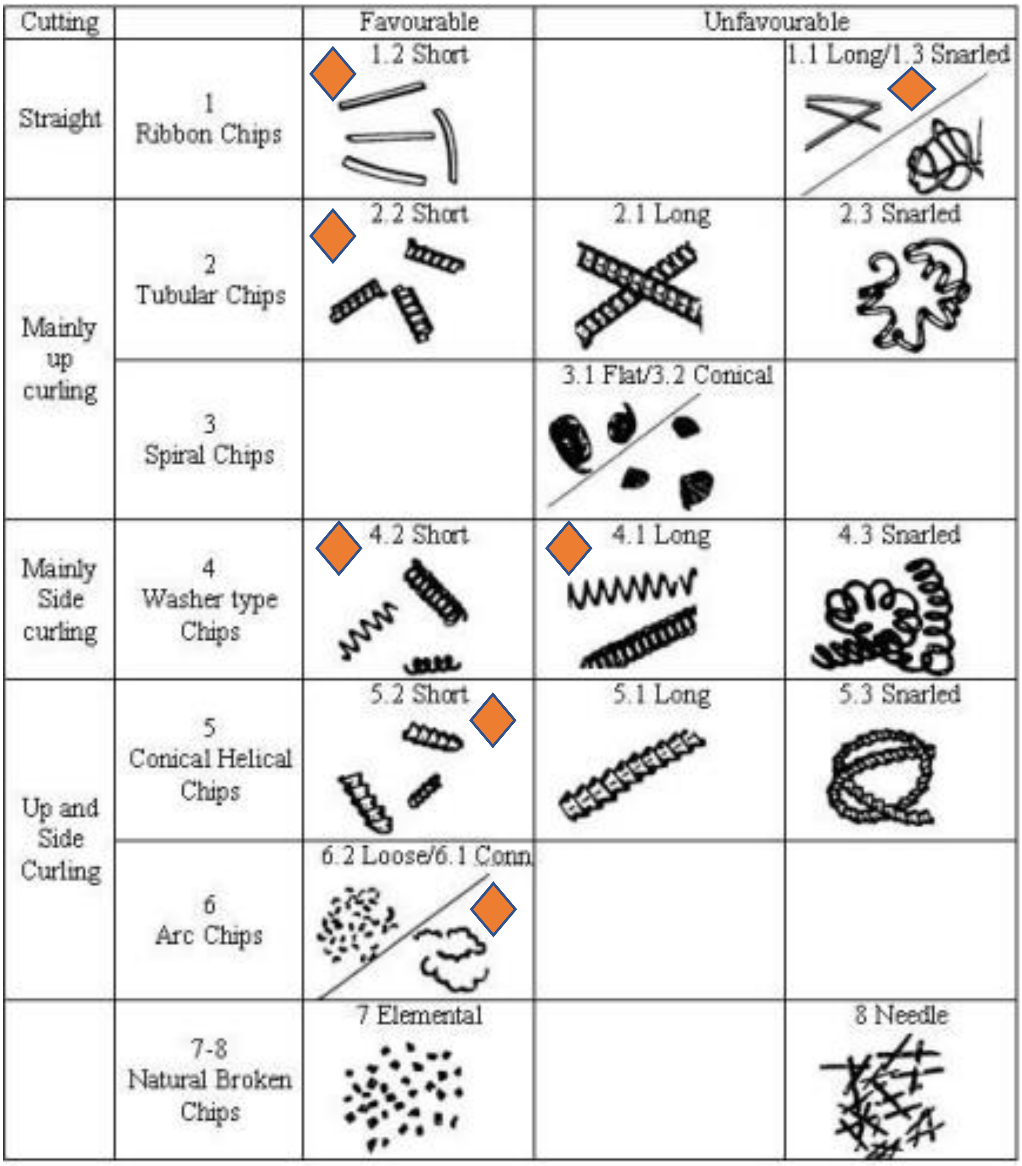
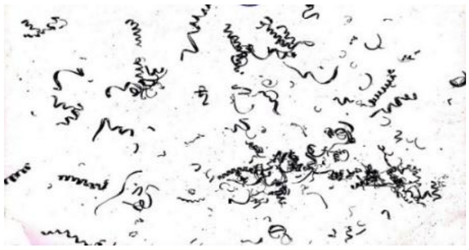
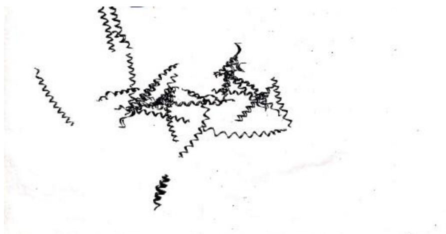


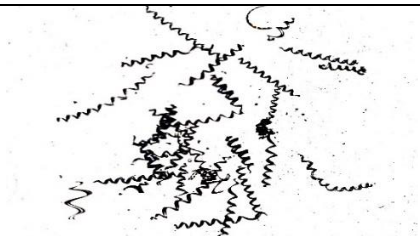
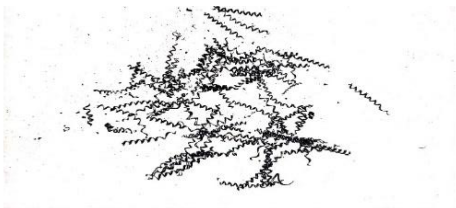
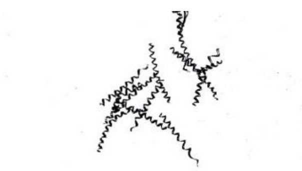
Figure 1. Chip form classification as per ISO 3685 standard [22] [23]

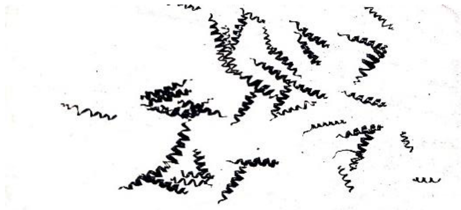
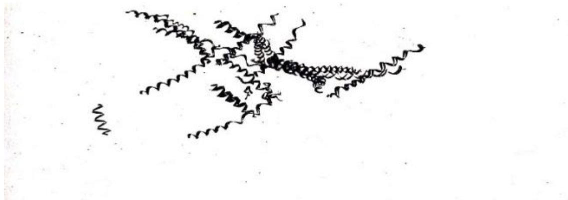
Chip formation can be quantified to assess the influence of factors such as cutting speed, feed rate, and depth of cut. The characteristics of the chips—such as color, shape, and size—are indicative of the chip-tool interaction and are affected by the machining environment. Therefore, maintaining the chip shape within a specific range can lead to better machining outcomes, including reduced thermal effects, extended tool life, improved tool wear performance, and enhanced surface quality etc. [21]

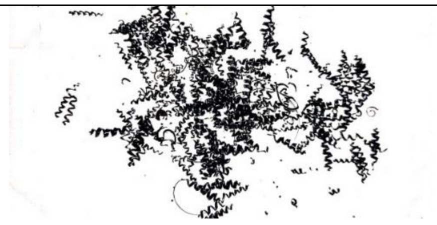
In this study, various types of chips were collected from machining experiments that utilized 17 different combinations of input parameters. Table 4 presents the chip formation in a matrix format, describing both the chip shape and color.

Table 4: Chip formation, Chip shapes and Chip color during hard turning of alloy steel EN19

S. No	Speed	Feed	DOC	Chip Shapes	Chip Colour	Chip
1	1500	0.125	0.15	Washer Type Helical Chips (Short) & Arc Chips	Metallic	
2	2000	0.0725	0.1	Ribbon Chips (Long)	Blue	
3	1500	0.025	0.15	Elemental Chips	Metallic	
4	1750	0.0725	0.15	Washer Type Helical Chips (Short)	Metallic	
5	1750	0.125	0.1	Washer Type Helical	Metallic	

				Chips (Short)		
6	2000	0.0725	0.2	Washer Type Helical Chips (Long)	Blue	
7	2000	0.025	0.15	Tubular Chips (Small)	Metallic	
8	1750	0.0725	0.15	Washer Type Helical Chips (Short)	Metallic	
9	1750	0.0725	0.15	Washer Type Helical Chips (Short)	Metallic	

10	1500	0.0725	0.2	Washer Type Helical Chips (Short)	Blue	
11	1750	0.0725	0.15	Washer Type Helical Chips (Short)	Metallic	
12	1750	0.125	0.2	Arc Chips (Loose & Connected)	Metallic	
13	1750	0.0725	0.15	Washer Type Helical Chips (Short)	Metallic	
14	2000	0.125	0.15	Washer Type Helical Chips (Short)	Partial Blue	
15	1500	0.0725	0.1	Washer Type Helical	Partial Blue	

				Chips (Short)		
16	1750	0.025	0.1	Ribbon Chips (Short)	Partial Blue	
17	1750	0.025	0.2	Ribbon Chips (Short)	Partial Blue	

After analyzing experimental results, five categories of chips were identified and classified into favorable and unfavorable groups. A summary of these classifications is provided in Table 5.

Table 5: Favorable and Unfavorable Chips

Type of Chips	**Favorable**	**Run No.**	**Unfavorable**	**Run No.**
Ribbon Chips	Short	16, 17	**Long**/Snarled	02
Tubular Chips	Short	07	Long/Snarled	------
Washer Type Helical Chips	Short	01, 04, 05, 08, 09, 10, 11, 13, 14, 15	**Long**/Snarled	06
Arc Chips	Loose and Connected	01, 12		
Natural Broken Chips	Elemental	03		

5. Conclusions

- The study concluded that the interaction among three process parameters—feed rate, cutting speed, and depth of cut—significantly impacts chip control and breaking.

- At high cutting speeds and medium feed rates, both long washer-type helical and ribbon chips were produced, which are considered unfavorable. In contrast, short chips are deemed favorable.
- At low feed rates, shorter ribbon, tubular, and elemental types of chips were formed.
- High feed rates and lower speeds resulted in arc chips when using medium and high depths of cut.
- The color of the chips changes from metallic to blue when the cutting speed increases due to heat generated at the tool-workpiece interface and carried away by the chips.

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