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Chip formation in turning S45C medium carbon steel in cryogenic conditions

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HIGHLIGHTS

- *Turning process of medium carbon steel S45C.*
- *Machining parameters of depth of cut and feed rate were found significantly affected the type of chip forms in machining S45C.*
- *Lower cutting force is expected with larger shear angle results as desired in machining industry.*

ABSTRACT

This paper presents the tribology issue regarding the chip formation in machining medium carbon steel (S45C) using a coated and uncoated carbide tools. The machining parameters under investigation were cutting speed, feed rate, and depth of cut under dry and cryogenic cutting condition using coated and uncoated carbide tools. The chip shape was largely depended on the combination of machining parameters, especially at high depth of cut and feed rate; the favorable chip was produced. Larger value of shear angle results in smaller shear plane area that provides benefits of lower cutting force needed to shear off the chips and lower cutting temperature being generated during the machining process.

Keywords:
| Medium carbon steel (S45C) | Chip formation | Turning process | Carbide tools |

1.0 INTRODUCTION

The chip formation is a result of tearing or pulling rather than cutting, which will affect the tool life, surface finish, and workpiece accuracy. Earlier findings reviewed by Zorev (1996), indicated that high speeds and heavy loads caused large changes in chip and cutting temperatures during machining. However, direct influence of the depth of cut on the chip formation process is insignificant, as well as at low cutting speeds. From the point of view of tribology, increasing the load leads directly to higher stresses, and this will result in more severe damage (Narutaki et al., 1997).

When machining hardened steels, workpiece material microstructure and thermal properties affect chip flow. It is common to observe that different thermal properties of the tool material may result in lower cutting forces (Fallbohmer et al., 2000). When machining hardened materials, continuous chip formation is observed at a conventional to high cutting speeds and low to moderate feed rates (Fallbohmer et al., 2000). At higher feed rates, ‘saw-tooth’ chips are produced. The latter type of chip formation can cause cyclic variations of both cutting and thrust forces and can result in high frequency vibration that affects tool life and tool failure. Fallbohmer et al. (2000) recent studies show that the formation of ‘saw-tooth’ chips is due to periodic formation of cracks at the head of the tool. The fracture on the surface of the workpiece propagates inside the chips until the stress state is altered from a low to a high compressive stress region. According to recent observations, the frequency of shear localized saw-tooth shape chips is very high. The cutting edge is subjected to a high frequency force variation. The chip formation certainly affects the cutting force. Segmented chips are produced by plastic instability, and they are responsible for reducing the cutting force (El-Wardany et al., 1996).

The effect of tool geometry on chip formation was investigated in the 1940s by Merchant (1945) covering two common types of geometry, which occur in cutting; His findings are still being referred by today researchers. Hirao et al. (1982) investigated the effect of chamfered tools; their qualitative observation found that the phenomena of chip formation using chamfered and nonchamfered tools were similar, except the thrust force is strongly affected and increases with both the chamfer angle and its length.

By controlling the contact area between the chip and the tool, Hsu (1966) showed the variation of the coefficient of friction in metal cutting. Changing in the size of the sticking region has been observed. The results also show that the force on the tool face varies with the depth of cut and the contact length. The variation of the normal and tangential forces influenced the stress distribution on the tool face. Boothroyd (1970) showed the work surface slope (rate of change of undeformed chip thickness) on the shear angle in metal cutting depends on the initial value of the shear angle and, hence on the cutting conditions.

In the present paper, the chip formed and coefficient of friction in turning S45C medium carbon steel was studied in detail in order to evaluate one of the machinability criteria of this material.

2.0 MATERIALS AND METHODS

The experimental works in this research were conducted on S45C carbon steel with original hardness of 59 HRB using a TORNADO CNC lathe machine (6000 rpm). Three different coated carbide inserts which have different values of rake angle were employed in the experiments. The turning experiments were conducted in dry condition. Table 1 shows the chemical composition of S45C carbon steel. The value of cutting speed (V_c), depth of cut (t), feed rate (S_o) and rake angle (α) is shown in Table 2.

Table 1: Chemical composition of S45C carbon steel (wt%)

C	Si	Mn	P	S
0.42 – 0.48	0.15 – 0.35	0.6 – 0.9	0.03 maximum	0.035 maximum

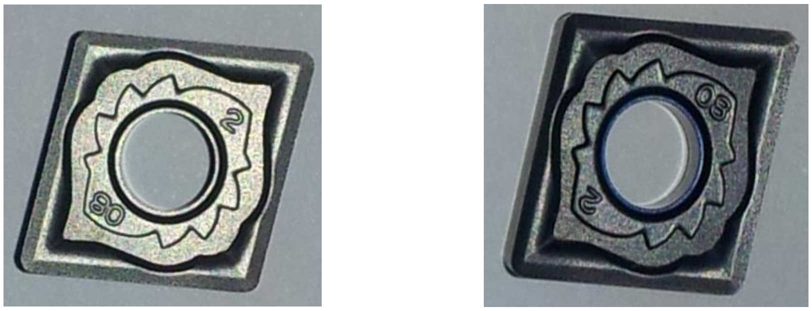
Table 2: Variable parameters used in the experiment

Workpiece material	Cutting inserts	Rake angle, *α* (°)	Cutting speed, *v* (m/min)	Feed rate, *f* (mm/rev)	Depth of cut (mm)	Cutting fluid
S45C carbon steel	CNGG 120408 H13A (uncoated) and CNGG 120408 SGF1105 (coated)	-6	120-140	0.2-0.5	0.5-1.5	Dry and cryogenic (LN_2)

The cutting tool used is a coated and uncoated carbide insert types of rhombus shaped from Sandvik as shown in Figure 1 (a) and (b) for uncoated and coated tools respectively.

Chips from both tests were then collected to closely examine the shape and chip thickness. The thickness of the chips was measured using a precision micrometer with accuracy of ±0.001 mm. Photographs of the chips were taken using an Olympus stereo microscope SZ61 with magnification range of 6.7x – 45x.

Measurement for cutting ratio was carried out by measuring the chip using a micrometer three times to get the average value. Figure 2 shows the schematic diagram of orthogonal metal cutting to show the relationships between shear angle and cutting ratio.



(a) (b)

Figure 1: Rhombus shaped of cutting tool (a) uncoated and (b) coated

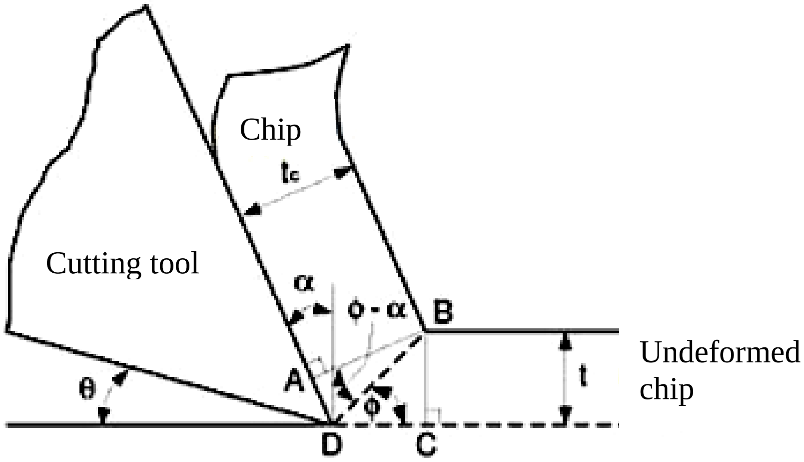


Figure 2: Model of orthogonal metal cutting

Using the measured value of chip thickness, cutting ratio of the cutting process can be calculated as in Equation (1) (Groover, 2010):

$$r = \frac{t_o}{t_c} \tag{1}$$

Where t_o is the undeformed chip thickness, and t_c is the measured chip thickness.

From the obtained value of cutting ratio and rake angle of the insert, shear angle was calculated using following Equation (2) (Groover, 2010):

$$\phi = \tan^{-1} \frac{r.\cos\alpha}{1 - r.\sin\alpha} \tag{2}$$

Where Ø is the shear angle, r is the cutting ratio, and α is the rake angle of the insert.

3.0 RESULTS AND DISCUSSION

The study of chip formation, including chip of machining medium carbon steel (S45C) had been widely carried out for the purpose to study of their effect on the tool life. Studies related to metal debris, including machining of medium carbon, S45C had been previously carried out to investigate the effect of the life of a cutting tool. A study by Lin et al. (1997) on metal matrix composites also associate with the beginning of the formation of crack's debris. The primary mechanism involves the initial formation of crack's debris from the outer surface free of debris caused by the high shear stress. The increase in cutting temperature resulted in a reduction of strength and hardness of the workpiece that occurs close to the cutting zone, that caused reducing the cutting force (Diniz & Micaroni, 2002).

Table 3 shows the experimental results obtained for various combination of machining parameters.

Table 3: Machining parameters and the experimental results

Experiment run	**A- Cutting speed, *v* *(m/min)***	**B- Feed rate *f, (mm/rev)* t_o**	**C- Depth of cut, *d* *(mm)***	**D- Type of Lubrication**	**E- Type of tools**	**Chip thickness , t_1 *(mm)***	**Cutting ratio, *r*, (t_o/t_1)**	**Shear angle, Φ**
1	120	0.2	0.5	dry	coated	0.39	0.51	48.49
2	160	0.2	0.5	dry	coated	0.37	0.54	49.72
3	200	0.2	0.5	dry	coated	0.36	0.56	50.43
4	240	0.2	0.5	dry	coated	0.335	0.60	52.22
5	120	0.2	1.0	dry	coated	0.4	0.50	89.71
6	120	0.2	1.5	dry	coated	0.41	0.49	69.25
7	120	0.3	0.5	dry	coated	0.455	0.66	44.42
8	120	0.4	0.5	dry	coated	0.535	0.75	40.36
9	120	0.5	0.5	dry	coated	0.6	0.83	37.23
10	120	0.5	1.5	dry	coated	0.808	0.62	57.17
11	240	0.5	1.5	dry	coated	0.805	0.62	57.17
12	120	0.5	1.5	dry	uncoated	0.83	0.60	56.48
13	120	0.5	1.5	cryogenic	coated	0.706	0.71	59.97
14	120	0.5	1.5	cryogenic	uncoated	0.745	0.67	58.93

Larger shear angle indicates smaller shear plane area and small value of a coefficient of friction that provides benefits of lower cutting force needed to shear off the chips and lower cutting temperature being generated during the machining process. ANOVA was performed to analyse the effect of the machining parameters on the shear angle for machining medium carbon steels in this study as shown in Table 4.

Table 4: Analysis of variance

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F
Model	1498.215	5	299.6431	3.414132	0.0602
A	19.60365	1	19.60365	0.223364	0.6491
B	765.397	1	765.397	8.72093	0.0183
C	1206.01	1	1206.01	13.74127	0.0060
D	2.073256	1	2.073256	0.023623	0.8817
E	5.648694	1	5.648694	0.064361	0.8061
Residual	702.1243	8	87.76553		
Cor Total	2200.34	13			

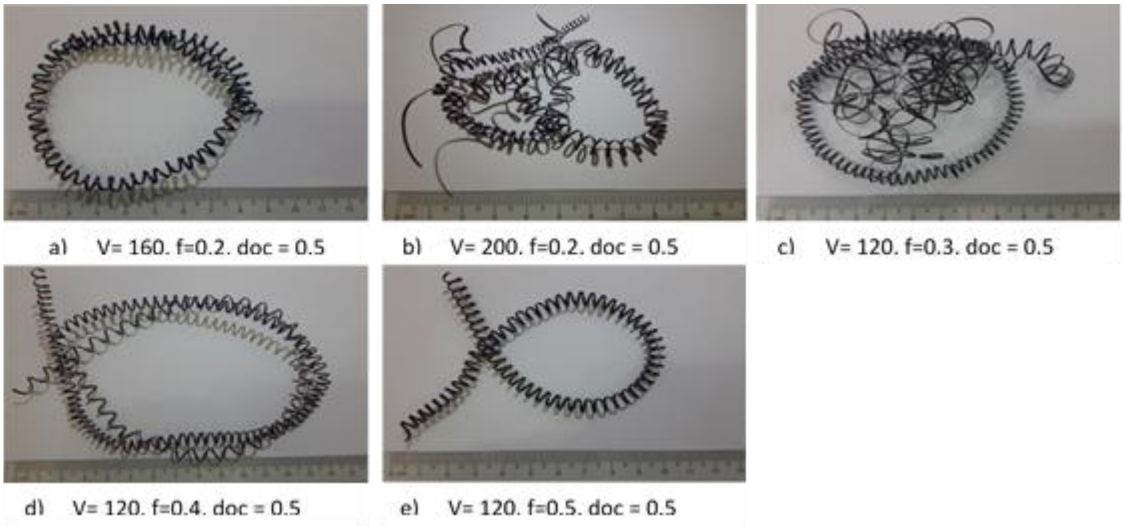
It was found that factor only factors B (feed rate), and C (depth of cut) is significant affecting the shear angle. Increasing feed rate and depth of cut resulted in increased in cutting forces (Korkut & Donertas, 2007), this can be explained by increasing chip cross-section with increasing feed rate and depth of cut. Friction force also increases due to the long tool–chip contact length.

May be due to the only few tests of cryogenic environments and uncoated tools that cause factors of feed rate and depth of cut are significant than other factors of cutting speed, type of tools and cutting conditions. However, comparing a result of shear angle for experiment no 12 and 14 found that the cryogenic resulted in bigger shear angle that indicates cryogenic turning decreases the contact length between the tool and the chip. Furthermore, according to Dhananchezian et al. (2009) because of better lubrication effect produced by the liquid nitrogen at the chip-tool interface due to the formation of fluid cushion and therefore, reduced the chip thickness in cryogenic machining resulted in the lowered cutting temperature and reduced adhesion between the tool and chip.

Studies of the shape of chip forms found that varying the cutting speed from 120 - 200 m/min and feed rate of 0.2-0.4 mm/tooth while kept constant the depth of cut at 0.5 mm resulted in similar chip shape as shown in Figure 3 of helical continuous long chips.

Figure 4 shows the shape of chip forms found that varying the cutting speed from 120 - 240 m/min and feed rate of 0.2-0.5 mm/tooth while kept constant the depth of cut at 1.5 mm. Similar chip shape of elemental discontinuous were produced except at low feed rate of 0.2 mm/tooth continues, short and ribbon-like shape was formed.

By comparing chips shape in Figure 3 and 4, it is clearly observed that the effect of depth of cut is significantly contributed to the chip forms followed by the feed rate. This finding is similarly obtained with the ANOVA performed. Preferred elemental shape was obtained at high depth of cut due to easy disposal by the operator. Furthermore, according to Natasha et al. (2014) the chips produced in cryogenic turning were thinner compared to those produced in dry turning. Thinner chip is also preferable due to easy disposal and produced high shear angle. Study conducted by Shankar et al. (2017) also found that vegetable based cutting fluids can lower the cutting force requirement and vibration.



a) V= 160. f=0.2. doc = 0.5

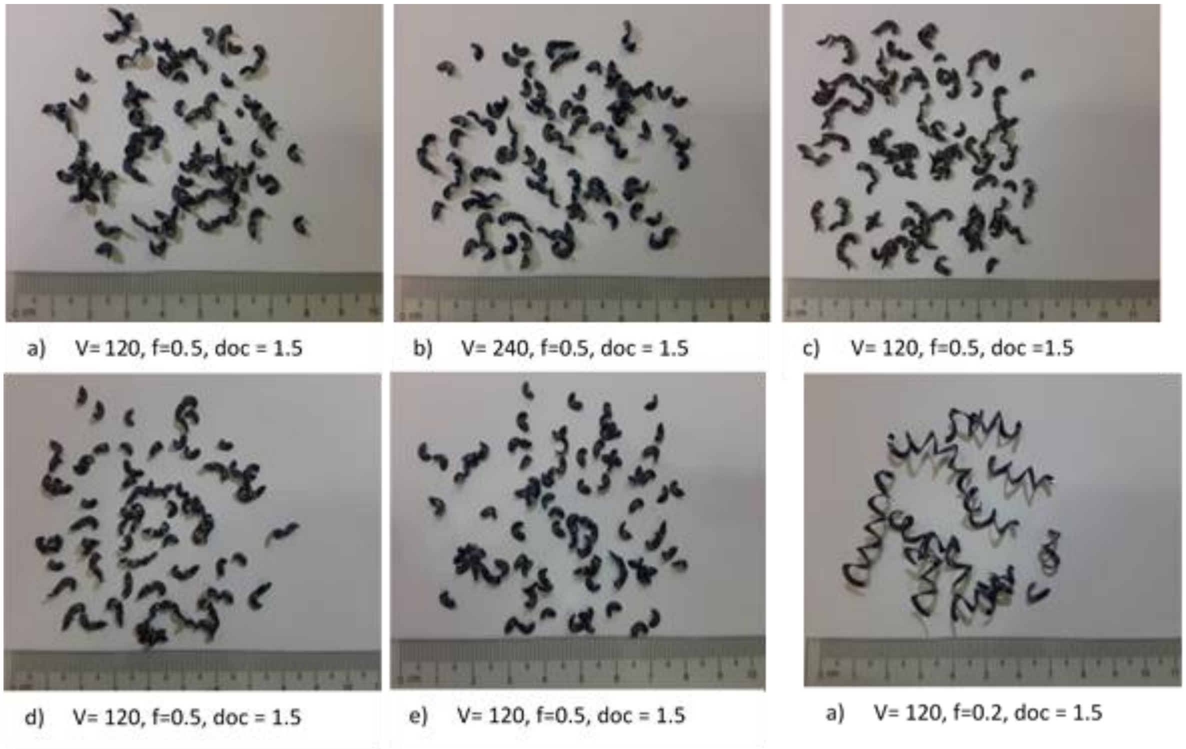
b) V= 200. f=0.2. doc = 0.5

c) V= 120. f=0.3. doc = 0.5

d) V= 120. f=0.4. doc = 0.5

e) V= 120. f=0.5. doc = 0.5

Figure 3: Chip shapes at cutting speed of 120 - 200 m/min and feed rate of 0.2-0.4 mm/tooth while kept constant the depth of cut at 0.5 mm.



a) V= 120, f=0.5, doc = 1.5

b) V= 240, f=0.5, doc = 1.5

c) V= 120, f=0.5, doc =1.5

d) V= 120, f=0.5, doc = 1.5

e) V= 120, f=0.5, doc = 1.5

a) V= 120, f=0.2, doc = 1.5

Figure 4: Chip shapes at 120 - 240 m/min and feed rate of 0.2-0.5 mm/tooth while kept constant the depth of cut at 1.5 mm

CONCLUSION

The machining parameters that affect the shear angle in this range of machining tests are the depth of cut followed by the feed rate. Larger shear angle resulted in smaller shear plane area and small value of a coefficient of friction that provides benefits of lower cutting force and lower cutting temperature being generated during the machining process of the medium carbon steel S45C. In addition, the cryogenic condition resulted in bigger shear angle and thinner chips compared to dry condition that indicates better lubrication. Elemental chip shape is desired in the machining process due to easy disposal by the operator.

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REFERENCES

Boothroyd, G., 1970. Effect of surface slope on shear angle in metal cutting. Journal of Engineering for Industry, 92(1), 115-118.

Dhananchezian, M., Kumar, M.P. and Rajadurai, A., 2009. Experimental investigation of cryogenic cooling by liquid nitrogen in the orthogonal machining process. International Journal of Recent Trends in Engineering, 1(5), 56-59.

Diniz, A.E. and Micaroni, R., 2002. Cutting conditions for finish turning process aiming: the use of dry cutting. International Journal of Machine Tools and Manufacture, 42(8), 899-904.

El-Wardany, T.I., Mohammed, E. and Elbestawi, M.A., 1996. Cutting temperature of ceramic tools in high speed machining of difficult-to-cut materials. International Journal of Machine Tools and Manufacture, 36(5), 611-634.

Fallböhmer, P., Rodríguez, C.A., Özel, T. and Altan, T., 2000. High-speed machining of cast iron and alloy steels for die and mold manufacturing. Journal of Materials Processing Technology, 98(1), 104-115.

Groover, M.P., 2010. Fundamentals of Modern Manufacturing Materials, Processes and Systems. Ed. 4. John Wiley & Sons Inc.

Hirao, M., Tlusty, J., Sowerby, R. and Chandra, G., 1982. Chip formation with chamfered tools. Journal of Engineering for Industry, 104(4), 339-342.

Hsu, T.C., 1966. A study of the normal and shear stresses on a cutting tool. Journal of engineering for industry, 88(1), 51-61.

Korkut, I. and Donertas, M.A., 2007. The influence of feed rate and cutting speed on the cutting forces, surface roughness and tool–chip contact length during face milling. Materials & Design, 28(1), 308-312.

Lin, J.T., Bhattacharyya, D. and Ferguson, W.G., 1998. Chip formation in the machining of SiC-particle-reinforced aluminium-matrix composites. Composites Science and Technology, 58(2), 285-291.

Merchant, M.E., 1945. Mechanics of the metal cutting process. I. Orthogonal cutting and a type 2 chip. Journal of applied physics, 16(5), 267-275.

Narutaki, N., Yamane, Y., Tashima, S. and Kuroki, H., 1997. A new advanced ceramic for dry machining. CIRP Annals-Manufacturing Technology, 46(1), 43-48.

Natasha, A.R., Ghani, J.A., Syarif, J., Che Haron, C.H. and Hadi, M.A., 2014. Comparison of dry and cryogenic machining on chip formation and coefficient of friction in turning AISI 4340 alloy steel. Applied Mechanics and Materials, 554, 7-11.

Shankar, S., Mohanraj, T. and Ponappa, K., 2017. Influence of vegetable based cutting fluids on cutting force and vibration signature during milling of aluminium metal matrix composites. Jurnal Tribologi, 12, 1-17.

Zorev, N.N., 1966. Metal cutting mechanics. Pergamon Press.