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ANALYSIS OF CUTTING FORCE AND CHIP MORPHOLOGY DURING HARD TURNING OF AISI D2 STEEL

X. M. ANTHONY

School of Mechanical and Building Sciences,
VIT University, Vellore – 632 014 Tamil Nadu, India
Email: manthonyxavior@vit.ac.in

Abstract

In this research work AISI D2 tool steel at a hardness of 55 HRC is being used for experimental investigation. Cutting speed, feed rate and depth of cut are the cutting parameters considered for the experimentation along with tool geometry namely, nose radius, clearance angle and rake angle. Three different cutting tool materials are used for experimentation namely multicoated carbide, cermet and ceramic inserts. The cutting force generated during the machining process is being measured using Kistler dynamometer and recorded for further evaluation. The chips produced during the machining process for every experimental trail is also collected for understanding the chip morphology. Based on the experimental data collected Analysis of Variance (ANOVA) was conducted to understand the influence of all cutting parameters and tool geometry on cutting force.

Keywords: Hard machining, Cutting force, Chip morphology, ANOVA,
Cutting parameter.

1. Introduction

In the recent past, great efforts were spent in understanding and simulating the hard machining process. This process allows manufacturers to machine hardened materials to their finish part quality without the aid of grinding, increasing the efficiency and decreasing the cost and processing time for post finishing. Recently, several steel alloys, such as AISI 52100 bearing steel, AISI 4340 and AISI D2 tool steel are machined by using this technology. Understanding the phenomenon of metal removal during hard machining is even more difficult when when compared to conventional machining, because the uncut chip thickness is very small (often lower than the tool tip radius), the cutting speed are high and the material hardness plays a major role on the chip segmentation, the surface integrity

Nomenclatures

d	Depth of cut, mm
Fc	*Cutting Force, N*
f	Feed rate, mm/rev
r	Nose radius, mm
t_{rs}	Transverse rupture strength of tool material, MPa
Vc	Cutting speed, m/min.
Greek Symbols	
α	Rake angle, degrees
γ	Clearance angle, degrees

integrity and the magnitude of the cutting forces. Guo and Yen [1] conducted a FEM study on mechanisms of discontinuous chip formation in hard machining. It was stated that the mechanism of discontinuous chip formation during hard machining is due to the internal crack initiation and extension in front of the tool and meeting with the surface crack.

Adiabatic shearing plays an important role in discontinuous chip formation. Mabrouki and Rigal [2] made some contribution towards a qualitative understanding of thermo-mechanical effects during chip formation in hard turning. It was shown that the velocity of the cutting phenomenon induces the material removal by adiabatic shearing corresponding to a localisation of the deformation in the chip. The latter is characterised by a thermal softening appearing in narrow periodic zones characterised by high straining levels. Consequently, the chip has saw-tooth morphology. El-Wardany et al. [3] presented an experimental investigation of the chip formation mechanism during machining of tool steel with PCBN tools. Umbrello et al. [4] had developed new flow stress models which include the hardness effect and used accordingly in computer simulation of hard machining. These models were found to predict well the cutting forces as well as the change in chip morphology from continuous to segmented chip as the hardness values change.

Dolinsek et al. [5] contributed to the understanding of chip formation mechanism in high-speed cutting of hardened steel. The analysis covered the chip segmentation frequency, chip shape and dimensions, and also the size of deformed and un-deformed parts of chip segments. The results showed that there exists a close relationship among these chip parameters. Poulachon and Moisan [6] had mentioned that saw-tooth chip is the result of some interrelated mechanisms such as localised shear, adiabatic shear and also as a catastrophic shear in the form of extensive cracks. Mohamed et al. [7] had reported that beyond 120m/min cutting speed, roughness (*R*a) is stabilised because of a reduction in the cutting forces at high speeds leading to a stability of the machining system during hard machining process. Investigations of machining of hardened steel have recently attracted a great deal of attention. The recent investigations in this segment of processes are focused on the four characteristic directions: mechanisms of tool wear, quality of surface finish, mechanisms of chip formations [8-10], and problems of machining of materials in their hardened state. Gaitonde et al. [11] investigated the influence of cutting speed, feed rate, and machining time on machinability aspects such as specific cutting force, surface roughness, and tool wear in AISI D2 cold work tool steel hard turning with three different ceramic inserts. It is also stated that the specific cutting force is also minimal for lower values of both cutting speed and machining time for all the three ceramic inserts. Shi and Richard [12] developed an FE model and predicted the chip formation and phase transformation in orthogonal machining of hardened AISI 52100 steel (62 HRC) using PCBN tools.

The chip-formation mechanism analysis is an effective tool for deeper understanding of cutting process. During hard machining, different mechanisms of chip-formation appear and this paper focuses on the analysis of chip segmentation frequency, chip shape and dimensions, and also the size of deformed and un-deformed parts of chip segments. The influence of cutting conditions for the variation in chip characteristics and parameters are analysed and reported in this research paper. Further, Analysis of Variance (ANOVA) was conducted to understand the influence of all cutting parameters and tool geometry on cutting force.

2. Experimentation

In this research work AISI D2 tool steel at a hardness of 55 HRC is being used for experimentation. Taguchi's L27 orthogonal array is used for design of experimentation. Cutting speed, feed rate and depth of cut are the cutting parameters considered for the experimentation. Tool geometry namely, nose radius, clearance angle and rake angle are also considered to have a comprehensive investigation on hard machining. Three different cutting tool materials are used for experimentation namely multicoated carbide, cermet and ceramic inserts. Tool geometry namely, nose radius, clearance angle and rake angle are also considered to have a comprehensive investigation on hard machining.

Three different cutting tool materials are used for experimentation namely multicoated carbide, cermet and ceramic inserts. Gedee Weiler MLZ 250V variable speed adjusting lathe is used for conducting the turning experimental trials. Cutting force generated during the machining process is being measured using Kistler dynamometer (Type 9257B: Piezo-multicomponent dynamometer with a measuring range of -5 to 10kN) The dynamometer output is coupled to a data acquisition system with the display unit, which gives the actual cutting force developed during the cutting operation. The cutting force values were observed and recorded for further evaluation. Figure 1 shows the experimental setup used for the experimentation. The figure shows the dynamometer used to the capture the cutting force generated during the process and the system used to store and process the data.

The chips produced during the machining process for every experimental trail is also collected for analysing using CARL ZIESS Optical Microscope having 50 X to 1500 X magnification, equipped with Clemex Vision Professional Edition Image Analysis Software to understand the chip morphology. Based on the experimental data collected Analysis of Variance (ANOVA) will be conducted to understand the influence of all cutting parameters and tool geometry on cutting force. Table 1 shows the experimental plan and the cutting force recorded for each trail of experiment.

Fig. 1. Experimental setup.

3. Results and Discussion

Based on the experimental observation Analysis of Variance (ANOVA) was conducted and it is shown in Table 2. From ANOVA it was found that depth of cut has more influence on cutting force followed by cutting speed. As the depth of cut is increased more friction is induced between the tool and workpiece which results in increase of the force required to complete the shearing operation. Beyond a certain level (120 m/min) of cutting speed, there is a rapid increase in cutting force for any depth of cut due to the combined effect of higher speed and more depth (larger contact surface area). Nose radius and clearance angle also have some considerable influence on cutting force. As the nose radius is increased the contact area between the tool and the workpiece is increased which results in more friction, subsequently increased cutting force. Likewise for every trail the chips formed were also collected and chip morphology study was performed. According to the design of experiments 9 trails each was conducted using carbide, ceramic and cermet inserts. Figure 2 shows the microscopic views of the chips collected for the experiments conducted with carbide insert. The matrix of the figure shows the 9 different types of chips collected from the machining experiments conducted using carbide inserts with 9 different combinations of other input parameters.

Two of the parameters namely cutting speed and feed rate are marked in the horizontal and vertical lines respectively for the convenience of presenting the chip morphology in the form of matrix. Accordingly, Figs. 3 and 4 shows the microscopic views of the chips collected for the experiments conducted with ceramic and cermet inserts respectively. The chip morphology was studied under an optical microscope to determine the thickness of the secondary deformation zone and the chip thickness. The secondary deformation zone's thickness at the tool-chip interface is an important factor in analysis of the cutting forces. The thickness of this zone depends on the depth of cut during the process which inturn determines the cutting forces generated and temperatures. Thus, the secondary deformation zone can be assumed to be the direction of maximum shear stress and maximum shear strain rate, and has the highest temperature in the chip. The lesser the secondary deformation zone the better the machining process. Each individual picture shows various dimensions of the chips like maximum, minimum thickness

Table 1. Experimental plan and observations.

S. No.	*Vc*	*f*	*d*	t_{rs}	α	γ	*r*	*Fc*
1	100	0.1	0.2	1400	6	0	0.4	150
2	100	0.1	0.2	1700	18	7	0.8	100
3	100	0.1	0.2	700	0	11	1.2	80
4	100	0.15	0.3	1400	18	7	0.8	200
5	100	0.15	0.3	1700	0	11	1.2	250
6	100	0.15	0.3	700	6	0	0.4	120
7	100	0.2	0.4	1400	0	11	1.2	400
8	100	0.2	0.4	1700	6	0	0.4	250
9	100	0.2	0.4	700	18	7	0.8	300
10	140	0.1	0.3	1400	6	7	1.2	150
11	140	0.1	0.3	1700	18	11	0.4	100
12	140	0.1	0.3	700	0	0	0.8	120
13	140	0.15	0.4	1400	18	11	0.4	250
14	140	0.15	0.4	1700	0	0	0.8	250
15	140	0.15	0.4	700	6	7	1.2	270
16	140	0.2	0.2	1400	0	0	0.8	150
17	140	0.2	0.2	1700	6	7	1.2	100
18	140	0.2	0.2	700	18	11	0.4	120
19	180	0.1	0.4	1400	6	11	0.8	150
20	180	0.1	0.4	1700	18	0	1.2	300
21	180	0.1	0.4	700	0	7	0.4	180
22	180	0.15	0.2	1400	18	0	1.2	150
23	180	0.15	0.2	1700	0	7	0.4	220
24	180	0.15	0.2	700	6	11	0.8	80
25	180	0.2	0.3	1400	0	7	0.4	300
26	180	0.2	0.3	1700	6	11	0.8	220
27	180	0.2	0.3	700	18	0	1.2	160

and the width of single segment in micrometers. Depending upon the machining conditions some differences in the chip morphology was observed. Strong oscillations of the forces occur, with a high absolute value of the force generated when material shearing is in progress and a lower value when a crack propagation is in progress and the discontinuous chip detaches from the workpiece [1]. The findings reveal that a strong relationship exists between the cutting force generated and chip formed during hard machining process.

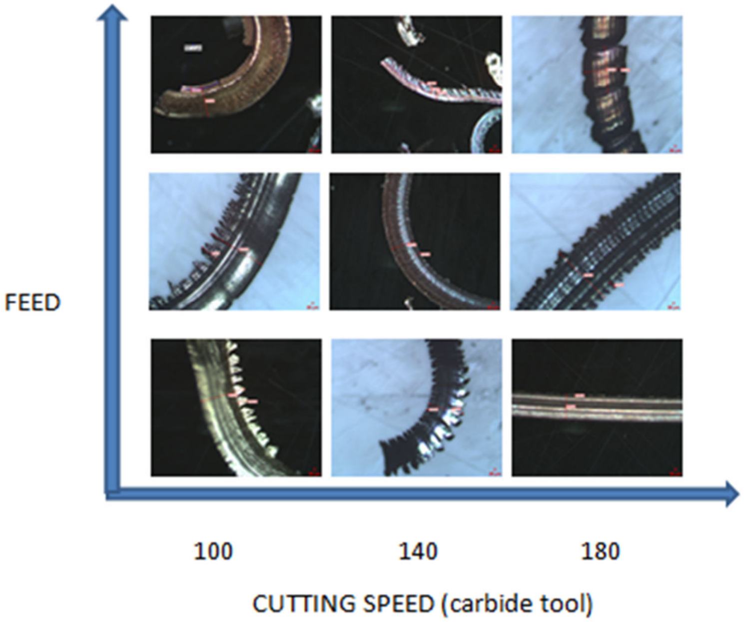

Fig. 2. Matrix of chips collected for carbide inserts.

Table 2. ANOVA for cutting force.

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Feed	1	0.88074	0.88074	0.88074	98.55	0.000
Depth of cut	1	0.03436	0.03436	0.03436	4.32	0.482
Cutting speed	1	0.00811	0.00811	0.00811	0.91	0.270
Nose radius	1	0.37807	0.37807	0.37807	47.44	0.113
Rake angle	1	0.60134	0.60134	0.60134	88.88	0.018
Clearance angle	1	0.00980	0.00980	0.00980	1.45	0.120
Transverse rupture Strength	1	174.22	174.22	174.22	12.79	0.002
Error	19	0.15750	0.15750	0.01313		
Total	26	1.16769				

***S = 0.0837826 R-Sq = 87.23% R-Sq (adj) = 84.90%**

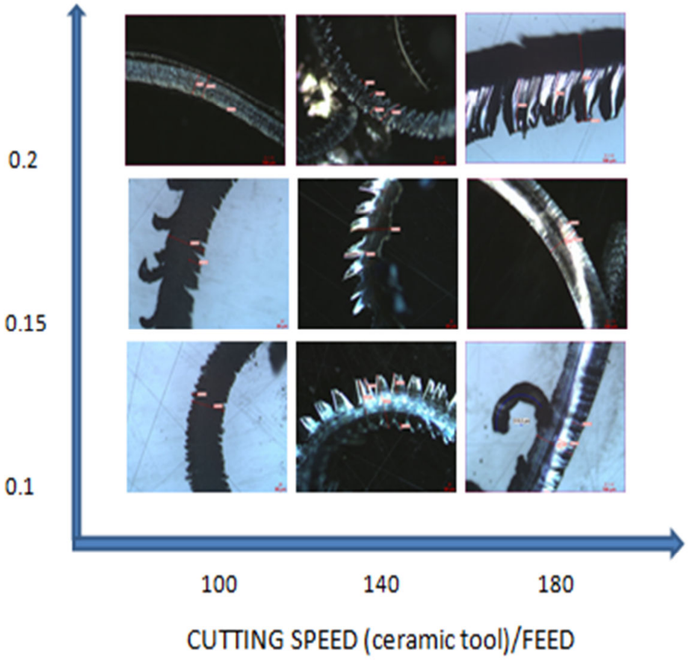

Fig. 3. Matrix of chips collected for ceramic inserts.

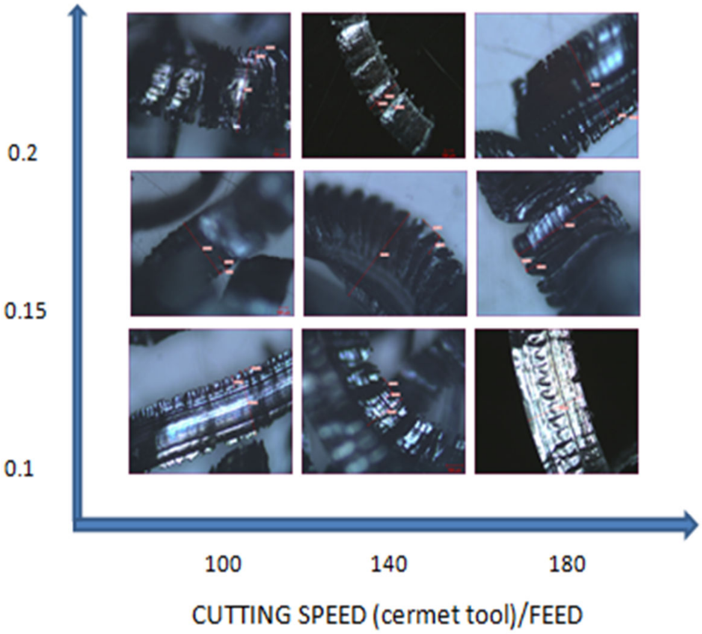

Fig. 4. Matrix of chips collected for cermet inserts.

4. Conclusions

One of the main characteristic direction for the investigations on hard machining is the mechanisms of chip formation apart from tool wear studies, surface quality and cutting force investigations. The chip formation mechanism analysis is an effective tool for deeper understanding of cutting process. This paper focuses on the chip morphology and cutting force investigations. Experimental investigations on hard machining of AISI D2 steel was performed using three types of cutting inserts under different machining conditions. ANOVA for cutting force was performed and it was found that depth of cut, followed by cutting speed influences cutting force considerably. Even nose radius and clearance angle contributes for the cutting force generated. It was also found that the tool materials have only meager influence on cutting force generated.

The chips studied after machining were found to be saw toothed at almost all cutting conditions inferring the high hardness of the workpiece. Based upon the chip shape evaluation obtained during the machining of the investigated steel the optimum cutting velocity for all the three inserts namely carbide, ceramic and cermet was found to be 140 m/min at keeping both feed and depth of cut constant individually as it provides the least secondary deformation zone, which indicates better machining quality. When the cutting speed is increased, the chip thickness and magnitude of chip segments decrease. Since cutting speed has considerable influence on cutting force and chip characteristic, it is also inferred that strong correlation exists between the cutting force generated and the chip morphology. The results show that there exists a close relationship between the cutting parameters on one hand and the chip morphology along with the other performance characteristics on the other hand.

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