Machinability Study using Chip Thickness Ratio on Difficult to Cut Metals by CBN Cutting Tool

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Abstract. Machinability is the one of the criteria in determining the life span of the cutting tool. In this experiment, hard and difficult to cut materials like hard AISI 440 C stainless steel and hard SCM 440 alloy steels were discussed. However, machinability of the material is considered to be poor due to its inherent characteristics. Machinability studies on AISI 440 C stainless steel and SCM 440 alloy steels had not been carried out by researchers. Machinability indices used in such cases have the characteristics such as cutting force, surface roughness, tool wear etc. In the case of high-speed machining of said materials machinability indices such as chip thickness (R_C), shear angle (Φ), surface integrity, and chip analysis are of prime importance. In this work, an experimental investigation was carried out to understand the behavior of difficult to cut materials, when machined using Cubic Boron Nitride (CBN) insert tool. The results and analysis of this work indicated that the above-mentioned machinability indices are important and necessary to assess the machinability of said materials effectively. The operating parameters used were cutting speed 100, 125, 150, 175 and 200 m/min with feed rate of 0.10, 0.20 and 0.30 mm rev^{-1} with constant depth of cut of 1.0 mm. The length of turning was 150 mm and 300 mm. Machinability of both materials and tool was evaluated in terms of roughness, flank wear, cutting force, chip thickness ratio and shear angle.

Introduction

Machining of hard materials is difficult by high speed steel tools, ceramic tools, even more difficult on material like titanium alloy, Inconel 718 and martensitic stainless steel etc. Few attempts have been made on the machinability of hard martensitic AISI 440 C and SCM 440 alloy steel with respect to chip thickness ratio, shear angle, and flank wear. Machinability is poor in turning stainless steel owing to low thermal conductivity, high ductility, high strength, high fracture toughness and high rate of work hardening. Work hardening of stainless steel occurred after a previous severe cutting operation by worn tools [1]. Sethilkumar et al. [2] turned hard martensitic stainless steel and found that it produced saw tooth chips in all operating parameters which increased the cutting forces. Liew et al. [3] conducted study on cutting AISI 420 steel using PCBN tool. The tool wear was found due to abrasion and cutting temperature. The porosity, ductility, and the bonding strength of the grains in the tool, apart from its thermal conductivity which have great influence on the fracture resistance of the tool. Fig.1. shows tool wear on single point tool. Machinability indices used here are chip thickness ratio, shear angle, tool wear, chip analysis was important. Experimental work was carried out to study the behavior difficult to cut materials like AISI 440 C martensitic stainless steel and SCM 440 alloy steel. There were no attempts or little consideration was given to evaluate the machinability with respect to chip thickness ratio and chip compression ratio and shear angle.

Experimental works.

Work materials. In this research, two work materials are used and they are hard AISI 440 C martensitic stainless steel and SCM 440 alloy steel. AISI 410, 420 and 440 A, B, C are all considered as martensitic stainless steel and can be hardened like other alloy steels. AISI 440 C is widely used in aerospace industries for bearings, steam and water valves, pumps, turbines, compressor components, shafting, cutlery, surgical tools, plastic moulds, nuclear applications etc. which demand high strength and high resistance to wear and corrosion [4]. It has high viscosity, poor thermal conductivity, low corrosion, high work hardening rate and tendency to form built up edge (BUE) at tool edge. AISI 440 C has high chromium and high carbon content and possesses high mechanical strength [5]. The materials were procured as 50 mm diameter rod and 1000 mm length. They were cut to 300 mm length and skin turned to remove oxide formation. The work pieces were centered on both sides to accommodate in the lathe centers. The heat treatment was carried out by induction hardening process on both materials. The hardness was maintained between

45 to 55 HRc. The cutting tool used is CBN tool. Tables 1 and 2 give chemical and operating parameters. The tool has rake angle of $-6°$, side rake $-6°$ and end clearance angle of $27°$ with nose radius of 0.80 mm. The SCM 440 material is best known as Cr-Mo. alloy steel. This grade steel is used in high tensile applications where wear resistance is of prime importance.
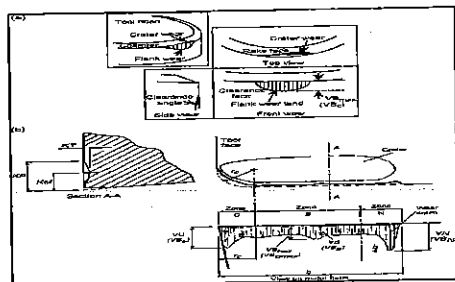

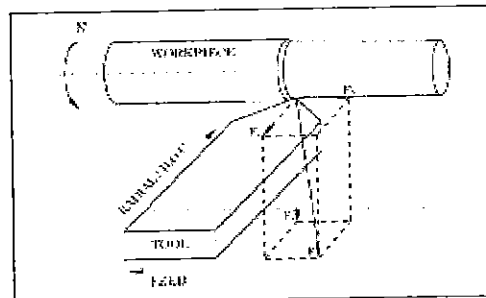Fig.1. Diagram various tool wear [4,5]

Fig.2. Forces acting on a tool [7]

Turning conditions. Turning tests were carried out on a high precision N.C. Harrison 450 lathe under dry turning conditions by varying cutting parameters such as cutting speed, feed rate and constant depth of cut of 1.00 mm. The cutting conditions used are presented in the table 1. The cutting forces component F_Y, feed force component F_X and radial or thrust force component F_Z were measured on line by Kistler dynamometer 9265 B with data acquisition system. Figure 2 shows the forces acting on a single point tool. Each trial the flank wear, crater wear and BUE were measured by Scanning Electron Microscope (SEM). The surface roughness was measured by Mitutoyo surface SJ 400 tester. The length of turning was up to 150 mm and repeated twice, each time surface roughness, tool wear and cutting forces were measured. It was decided that maximum flank wear of 0.30 mm as per ISO 3685 – 1977 standard and the experiments were stopped once it reached the set value. The graphs shown are for 150 and 300 mm length only. The chip thickness was measured using vernier caliper.

Table 1. Chemical properties of materials

Alloying elements	AISI 440 C	SCM 440
Carbon	0.95-1.20	0.35-0.43
Manganese	1.00	0.75-1.00
Chromium,	16-18	0.75-0.80
Molybdenum	0.75	0.15-0.25

Table 2. Operating parameters

Cutting velocity- m /min	100, 125,150, 175, 200
Feed rate - mm/rev	0.10, 0.20 and 0.30
Depth of cut – mm	1.00

Results and discussion.

Surface roughness. Many researchers have conducted study on the surface roughness with different parameters and found that the roughness decreased with the increase of cutting velocity for given feed rate and depth of cut. The roughness increased with feed rate and depth of cut. Even though, stainless steel is tough and difficult to cut material, it produced low surface roughness value at high cutting speed and low feed rate by CBN tool, corresponding to SCM 440 alloy steel produced marginally high value at the same operating parameters as that of stainless steel. It indicates that the plastic deformation by stainless steel is more than alloy steel. The results agreed with general trend low value of roughness as the cutting velocity was increased for a given feed rate and depth of cut. The value obtained for 150 mm length was lower than by 300 mm length in alloy steel turning than stainless steel. When turning stainless steel there were formations of erratic built up edges (BUE) and this increased the roughness. At high cutting speed the BUE vanished. The surface roughness was obtained on SCM 440 alloy steel was high than stainless steel. Figure 3 (a) and (b) shows the graphical representation of surface roughness for 150 and 300 mm length of turning. As the cutting speed increases, roughness is lower in turning stainless steel than alloy steel for a given feed rate and depth of cut. Even though, stainless steel is tough in turning than alloy steel, the plastic deformation of stainless steel is more than alloy steel which was responsible for the results.
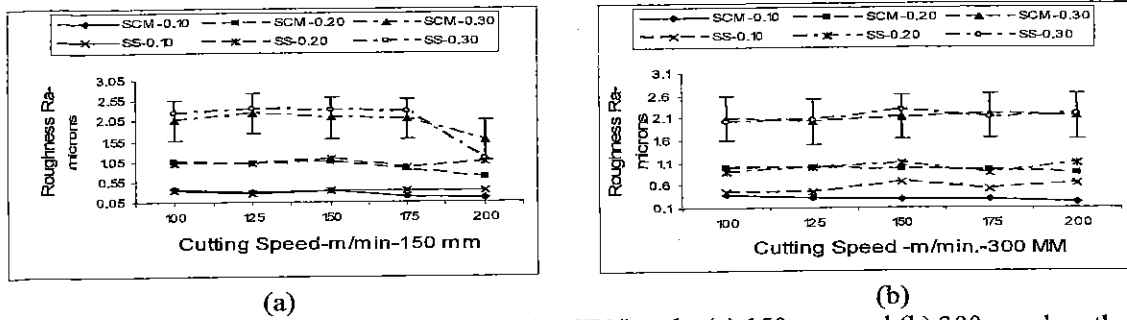
(a)   (b)

Fig.3. Cutting speed Vs Surface roughness by CBN tool - (a) 150 mm and (b) 300 mm length of turning.

It is shown in the figure 3 (a) and (b) that surface roughness decreases as the cutting velocity increased for low feed rate of 0.10 mm rev^{-1}.

Cutting force F_Y. A force is required to remove material or cause deformation. Forces can be used as reference to predict other output parameters such as tool wear, surface roughness and tool life that will lead to enhance the machining accuracy and efficiency, whereby improved machining can be realized and tool life can be extended during turning. There are three cutting forces acting on tool which is shown in the figure 2. The force acting on along the direction of tool travel is feed force F_X, force acting perpendicularly downwards is termed as cutting force F_Y and force which keeps the cutting tool in direction normal to work piece axis is termed as radial force F_Z. In our study, the cutting force F_Y was considered for the analysis. Tool wear usually influences the cutting forces because it changes the geometry of tool; alter the cutting edge condition of tool and the surface finish of the work piece. Saglam et al. [6] reported that the temperature at cutting zone depends, to a large extent, on the contact between tool and chip, the magnitude of the cutting forces and the condition of friction between tool and work piece material. Excessive heat will cause undesirable high temperature in the tools which leads to softening of the tool and its accelerated wear and breakage. When the cutting speed was low at 100 m/min, the cutting force was high while turning alloy steel than stainless steel. As the cutting speed increased, within a short time the materials removal take place this in turn increased deformation. The deformation heat generation which soften the chips and there by reduced the cutting force at high cutting velocities. The stainless steel is less conductor of heat and heat was completely shared by chips which were responsible for softening and thus less force. In turning, alloy steel, the heat generated by alloy steel was shared by the tool work material, cutting edge and chips. So, the softening of the chip was less and cutting force was high in turning alloy steel. The flank wear of the tool also helps to increase the heat in stainless steel than alloy steel. Figure 4 (a) and (b) is the graphical representation of cutting forces for 150 mm and 300 mm respectively. In turning stainless steel, the cutting forces was low than alloy steel due to softening effect of chips. Softening of chips helps to deform material and hence low cutting force. While turning alloy steel, heat was shared by chips, tool edge and work material and the heat is not enough to soften the chips.
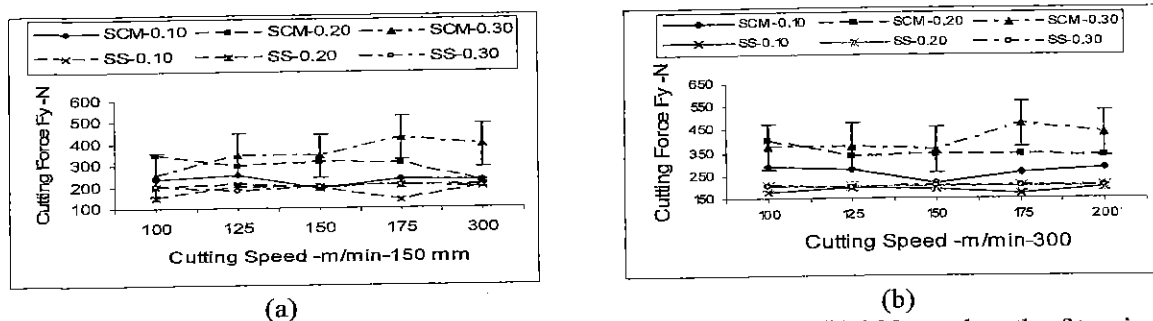

(a)   (b)

Fig.4. Cutting speed Vs Cutting force by CBN tool - (a) 150 mm and (b) 300 mm length of turning.

Chip thickness ratio - Rc. It is important in evaluating the heat and degree of deformation during turning process. It is measure of efficiency of chip formation [7]. The chip thickness ratio can be calculated using depth of cut and final deformed chip thick. i.e. it is the ratio of un-deformed chip thickness t_o to deformed chip thickness t_c.

$$Rc = \frac{to}{tc}$$

Eq.1

The un-deformed thickness can be considered as equal to feed rate and actual thickness can be measured by vernier caliper or micrometer.

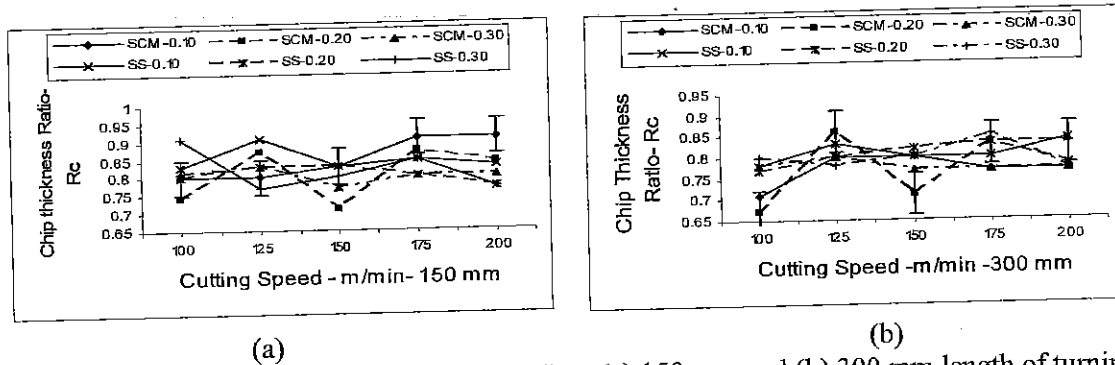(a)   (b)

Fig.5. Cutting speed Vs Chip thickness ratio R_C - (a) 150 mm and (b) 300 mm length of turning

At low cutting speed, the chip thickness was high for both materials generally at low feed rate. As the cutting speed increased with feed rates, the chip thickness of stainless steel reduced than alloy steel for both feed rate 0f 0.20 and 0.03 mm rev^{-1}. It was generally observed that as cutting speed increased the chip thickness decreased. At low cutting speed, due to large contact area on the rake face and small shear plane angle thick chips are generated. Small contact area and larger shear plane angle reduces the cutting forces. Form the figure 5, (a) and (b), it was clear that feed rate resulted in increased pressure on the tool causing plastic deformation of work materials. Therefore, it was observed that chip thickness increased with increased in cutting speed. This resulted in the chip thickness ratio R_C. A low value of chip thickness ratio leads to higher degree of shear plane angle Φ, which turns leads to low share strain in the chip and reduce energy consumption. When the cutting speed increased, the region of the plastic deformation becomes smaller. It is observed in general that as the cutting speed increased the chip thickness ratio reduced.

Shear Plane angle- Φ. The basic mechanism of chip formation involves localized shear deformation of the work material ahead of the tool cutting edge. Shearing takes place over very narrow regions of the primary shear zone inclined at the so-called shear angle (Φ). The work material is further subjected to extensive plastic deformation in the secondary shear zone adjacent to the chip–tool interface and in the tertiary shear zone over the tool flank. Once the shear angle is defined, all the other process parameters could be predicted. Shear angle (Φ) dominates the cutting forces, and it is calculated using following relationship [8 & 9]:

$$Tan\phi = \frac{RcCos\theta}{1 - RcSin\theta}$$

Eq.2.

where cutting ratio (Rc) = t_o / tc, to is the uncut chip thickness and t_C cut chip thickness, θ is the rake angle of the tool and Φ shear angle. The shear angle is inversely proportional to the chip compression ratio, with the increase of cutting speed the shear angle also increased. Increase in the cutting speed with feed rate, the shear angle also increased and it is shown in the figures 6 (a) and (b). The reason behind this phenomenon is that at constant cutting tool geometry, the shear angle is inversely proportional to chip compression ratio and decreased or nearly less increased. Higher shear angle is having relationship with low cutting force. Increase in cutting velocity for the given feed rate increases the shear angle, which resulted in shorter shear plane. By referring the cutting

forces graph Figure 5 (a) and (b), higher the cutting speed, low cutting forces for the given feed rate due to the high energy input to the cutting system strain rates are high. The cutting forces reduced due to the heat generated during machining which plasticize the chips and forces low. The heat reduces the strength of the work materials. When the shear angle is increased, very thin chips are produced due to heat as well as by the reduction in material strength. When the chips are thin in sizes chip speed is increased. The shear plane angle at low cutting speed with low feed rate is high and reduced as the speed increased. This is the trend for both materials.

Effect of cutting parameters on tool wear. Tool wear is a normal phenomenon occurring in any metal cutting process and considered to be undesirable especially, if it is excessive. A study of the nature of wear of a tool helps in gaining cutting efficiencies and evaluation of its performance. An understanding of failure mechanisms directs new research into the development of more desirable materials ultra hard materials. The life of cutting tool is largely dependent on the tri-bological characteristics of the machining process such as tool work interface friction and associated forms of tool wear such as flank wear and crater wear. The flank wear is the most important because it raises cutting forces and related problems. Figure 7 (a) and (b), it was observed that as the cutting speed was increased, the flank wear also increased correspondingly. These forms of tool wear are associated with various mechanisms listed above. In metal cutting, tool flank wear is strongly influenced by the interactions between cutting tool and work piece in the form of contact stress and cutting temperature. When machining stainless steel, the flank wear increased rapidly compared SCM 440 alloy steel. Formation of built up edges were also seen at flank side of the tool while machining stainless at early stage of turning. Formation of built up edges are common phenomenon in machining difficult to materials and stainless 440 C is no exception.
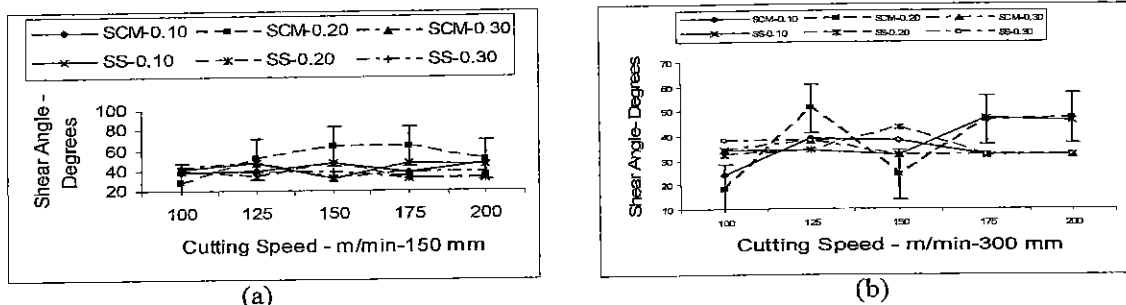

Fig.6. Cutting speed Vs Shear angle Φ - (a) 150 mm and (b) 300 mm length of turning.

The rapid increase in the flank wear also influences the cutting forces due to heat at cutting zone. Deeper crater wear was formed by stainless steel due to movement of saw tooth chips.
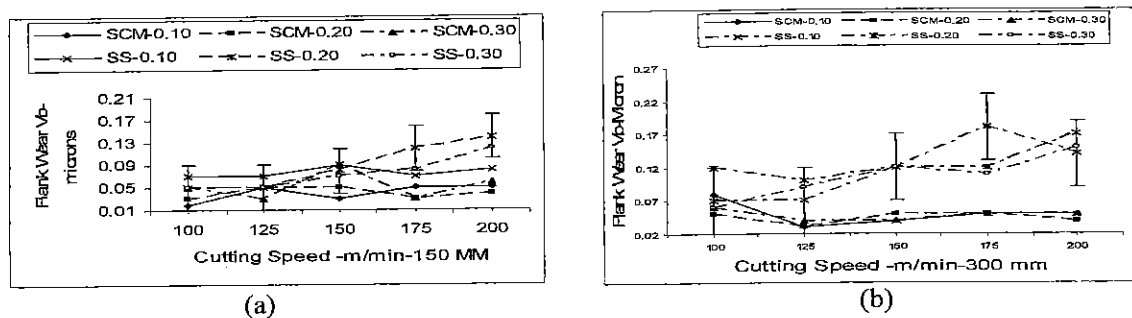

Fig.7. Cutting speed Vs Flank wear - (a) 150 mm and (b) 300 mm length of turning.

Conclusions.

Based on the performance and test results, of the various set of experiments performed to analyze the influence of cutting parameters on the machinability characteristics of AISI 440 C martensitic stainless steel and SCM 440 alloy steel, the following conclusions are drawn:

1. At higher cutting speed with low feed rates, the machined surface was smooth. This is achieved in this experimental work also. The surface becomes rough at high feed rates.

2. The chip compression ratio can be used as one of the important machinability characteristics and it represents energy consumed in metal cutting on plastic deformation. The plastic deformation in machining stainless steel was found to be higher due to work hardening ability.

3. The shear angle increased when cutting speed increased. This may be indirect indication of the machinability parameters like cutting force, chip thickness ratio, chip –tool contact length, temperature etc.

4. In the machining of stainless steel the formation of flank wear was due to abrasion. As the speed increased, rapid wear occurred on the flank side of the stainless steel compared to alloy steel.

Acknowledgement.

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