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Effects of single point cutting tool materials on tool work interface and cutting performance using FEA

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Abstract. The purpose of this work is to come to a conclusion about the best cutting tool material for mild steel machining using a single point cutting tool. In a single point cutting tool, the geometry of cutting tool affects the quality of manufacturing process. The chip formation process involves plastic deformation during which large strains and strain rates are developed by shear deformation of work material immediately ahead of tool. Mild steel (low carbon steel) is used for machining and insert materials for single point cutting tool are of cubic boron nitride (CBN-grade tnma160408) (used for both finishing and roughing), cermet insert (for finishing), carbide insert (for roughing). For determining the best cutting tool material among three above mentioned cutting tools, the cutting performance is observed by machining of mild steel done in the machine shop. For the improvement of cutting performance, the knowledge of cutting forces, temperature at the tool-work interface and time of cutting with good accuracy is essential which is done by FEA analysis using ABAQUS software [1]. Because of nature and constants of the metal cutting and insert used, heat is generated during the chip formation process as a result of plastic deformation, heat conduction and friction. The heat influences chip shape, tool wear, surface finish and cutting forces, which also effects the hardness of insert material before and after the turning process on work-piece. Various effects of single point cutting tool materials on tool work interface and cutting performance are studied using FEA.

1. Introduction

In industries, in the field of manufacturing, the surface finish quality of the product depends upon various parameters of the work-piece and the cutting tools used along with the functioning of various components of the CNC machine in use. A lot research is done in the field of manufacturing to decrease the time of machining and increase the surface finish. The product quality depends upon the work done by the tool – roughing or finishing of the work-piece material using that tool. Roughness and finishing are two different design features depending upon the constraints and tolerances for the work-piece and tool material selection and interaction. The selection of the process parameters done after selection of the work-piece and tool material is done considering the best surface finish and least tool wear with high material removal rate. The material removal rate depends upon the micro geometrical parts and functional behavior during the interaction of the work-piece and cutting tool for chip formation.

The chip shape formed in the different cutting interactions depends on various parameters like cutting forces, depth of cut and feed rate. The chip shape is also influenced by the heat generated in the interaction and this also sometimes causes chip welding to tool surface forming built up edges on tool causing tool wear and decrease in life of tool. By using finite element analysis of the mesh and chip formation, simulation can be done and thus the prediction of the formed chip can be realized and conclusions can be made.

For the chip simulation, abaqus software is used in which the interactions are done by making mesh of the work piece and cutting tool inserts. The simulation can further provide a preventive quality assurance and the problems can be predicted and avoided if we accurately represent the cutting process and interaction with machine tool. Finally, the results are compared with the model made in the abaqus software including the work-piece and the cutting tool [1].

2. Materials

For machining and chip formation processes we have selected metal mild steel (low carbon steel) for metal cutting and the selected insert materials for single point cutting tool are of cubic boron nitride (CBN-grade tnma160408)(used for both finishing and roughing), cermet insert (for finishing), carbide insert(for roughing).

2.1 Work-piece - Mild steel

Mild steel is selected as work-piece as it has greater resistance to oxidation in presence of oxidizing gases formed during the residual stresses of chip formation, also the heat generated does not have too much harmful influence on the mechanical properties of mild steel. Mild steel is low carbon steel; it consists of C-0.13%, Mn-0.6%, Si-0.11%, Al-0.1% [2]. Carbon and manganese present in mild steel increase hardness and silicon and aluminum act as deoxidizing agents. The brinell hardness number of mild steel is 126 and Rockwell hardness number is 71.

For the tool material, inserts selected are of grade TNMG 160408 – triangular shape, with negative clearance angle, medium tolerance angle, granular or abrasive type, cutting tool length of 16.5mm, thickness 4mm and nose radius of 0.8mm.

2.2 Inserts

The carbide insert selected provides a high hardness for a wide range of temperature and thus provides a good cutting speed with high wear resistance. It has low thermal expansion and less thermal conductivity than steel [3].

The cermet insert selected is a sintered ceramic of titanium carbo-nitride used for high speed cutting operation [4]. They are hard phased bonded metallic binders which are tough and ductile, so they provide continuous chip formation.

The cubic boron nitride insert selected is a nano-sized crystalline structure which is suitable for both roughing and finishing operations. It has high surface roughness and a lower value of stiffness than other crystalline materials due to morphology and nucleation [5].

All the insert materials selected have young's modulus more than mild steel which helps the cutting inserts to undergo more stress than the mild steel for a respective equal strain during the interaction, which helps cutting forces over a wide range of depth of cut and feed rate.

The young's modulus (E) and Poisson ratio (v) of the materials are shown in the table below [3] [4] [5], the other constants like bulk modulus (K) and shear modulus (G) were calculated by formulas E=2G (1+v) and E=3K (1-2v) [6] and verified as shown in table 1.

Table 1. Properties of materials selected.

Material	Young's modulus (E)(GPA)	Poisson ratio (v)	Shear modulus (G)(GPA)	Bulk modulus (K)(GPA)
Mild steel	205	0.29	78	140
Carbide	530	0.31	274	630
Cermet	400	0.23	162	256
Cubic boron nitride	587	0.15	255	279

2.3 Chip formation

For the chip formation in machine shop, machining was done at different depth of cut and feed rate variations at a constant speed of 500rpm. In machining metals and alloys, chip removal is performed by abrasives or by cutting tools having distinct cutting edges. A single point cutting has various edges and thus finds wide application on lathes, shaping and slotting machines. The two basic methods of chip formation using a single point cutting tool is orthogonal cutting and oblique cutting. Orthogonal cutting takes place when the tool is at 90° to the line of action, or the rake angle is zero. At angles of cutting less than 90° it is oblique cutting process. The cutting force in the single point cutting tool depends on the proper design of cutting tool, power and distortion of the work piece.

The heat generation is related to the plastic deformation, shearing and friction. The chip takes around 60%-80% of the total heat generated, about 10% affects the tool and the rest affects the work piece. The coolant used during cutting process can remove around 90% of the heat affecting to tool and work piece thus decreasing tool heating and wear. In metal cutting, types of chips formed are continuous, discontinuous and chips with built up edge [6].

Discontinuous chips are formed during the machining of a brittle material, or by cutting a ductile material using a cutting fluid, large thickness chips are formed which are small in length. They are formed at low cutting speed and small rake angle. The continuous chip are smooth chips formed in ductile material, these chips have small chip thickness. They are formed at high cutting speed and small rake angle. The chips formed have a uniform thickness throughout due to stable cutting, this results in good surface finish. They are difficult to handle and dispose off.

The continuous chip with a built up edge is not smooth. At high temperature the chip rising past the tool get welded to the tool and increase the tool wear.

3. Machining data

Table 2. Chips formed during machining of mild steel.

S/n	Material	Spindle speed (rpm)	Feed rate(mm)	Depth of cut(mm)	Observation
1	Carbide	500	0.15	1	Small thickness, continuous and discontinuous chips
2			0.25	1	Small thickness, continuous and discontinuous chips
3			0.15	0.5	Small thickness discontinuous chips
4			0.25	0.5	Small thickness, fine discontinuous chips
5		750	0.15	1	More thickness, long discontinuous chips
6			0.25	1	More thickness, continuous and discontinuous chips
7			0.15	0.5	More thickness, short discontinuous chips
8			0.25	0.5	More thickness, fine discontinuous chips
9	Cermet	500	0.15	1	Very fine, long discontinuous chips
10			0.25	1	very fine and short discontinuous chips

11			0.15	0.5	very fine and long discontinuous chips
12			0.25	0.5	very fine and short discontinuous chips
13		750	0.15	1	More thickness, short discontinuous chips
14			0.25	1	More thickness, long discontinuous chips
15			0.15	0.5	More thickness, short discontinuous chips
16			0.25	0.5	More thickness, long discontinuous chips
17	Cubic boron nitride	500	0.15	0.25	Continuous long length chips
18			0.1	0.25	Continuous long length chips
19			0.15	0.5	Discontinuous short chips
20			0.1	0.5	Discontinuous short chips

4. Discussion on inserts

4.1 Carbide insert

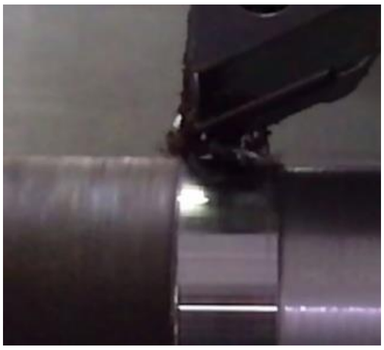

Figure 1. Carbide with built up edge.

Figure 2. Small discontinuous chips.

The machining of mild steel using carbide insert provided small thickness discontinuous chips as in figure 1, with built up edge at less spindle speed (500rpm) as shown in the table 2. As the depth of cut is increased, it is observed that both continuous and discontinuous chips start to form but in small thickness. These discontinuous chips formed are preferred for roughing purposes along with the embedding of chip to the tool surface. The built up edge as shown in figure 1 is formed during machining at less speed which causes tool wear [7].

At high spindle speed (750rpm) more thickness, long length and fine discontinuous chips were observed as shown in figure 2, without built up edge, so there is less tool wear. So a lower spindle speed is more optimum for carbide roughing purposes [2] [5]. At higher spindle speed less depth of cut, more thickness but short and fine discontinuous chips are seen, and at more depth of cut long discontinuous chips are seen which show an increase in roughness by increase in depth of cut.[8]

4.2 Cermet insert

Figure 3. Fine discontinuous chips.

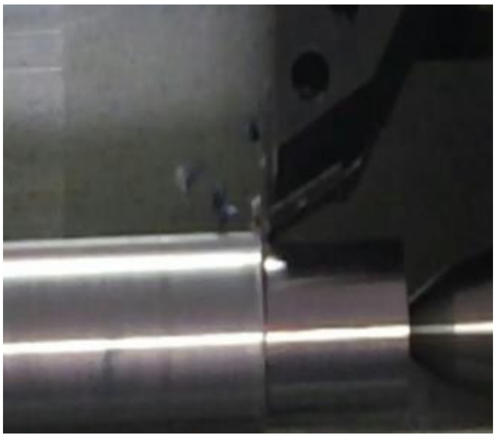

Figure 4. Cermet material.

The machining using cermet insert provided fine, discontinuous chips with very smooth operation and surface finish at less cutting speed (500 rpm) as shown in the table 2 and figure 3 and 4. As the feed rate is increased from 0.15mm to 0.25mm the chips length decrease from long to short. These fine small thickness short chips show that cermet can be used for finishing process as seen it also provided good surface finish of mild steel [3]. There is no built up edge seen while machining so the tool wear is less along with a superior micro finish. And it can also be concluded that the increase in feed rate is dominant for the surface finish. [8]

At high spindle speed (750 rpm) more thickness short discontinuous chips are observed initially, as the feed rate increases at a constant spindle speed, the long discontinuous chips formation is observed. The chip is nicely broken with small and normal chip helix, no embedding with tool face to cause tool wear, and as preferred for grinding purposes, the chip is fine and small.

4.3 Cubic boron nitride insert.

Figure 5. Cubic boron nitride.

Figure 6. Long continuous chips.

The machining of mild steel using cubic boron nitride was done only at 500rpm. Cubic boron nitride is a very hard material and is preferred to be used only for the roughing and finishing purposes of hard materials of grade more than HRC 50. Mild steel has hardness of HB 126. The machining yet provided chips for variation of feed rate and depth of cut. At less depth of cut of 0.25mm, continuous long length chips were observed as shown in the figure 6 , these continuous chips show that the machining was smooth[8] and the work-piece underwent uniform compression and shear during the interaction, making cubic boron nitride suitable for finishing purposes. On increasing the depth of cut to 0.5mm, discontinuous short uniformly broken chips are observed. These discontinuous chips formed are preferred for roughing purposes along with no embedding of chip to the tool surface as no built up edge was observed during machining with mild steel. [4]

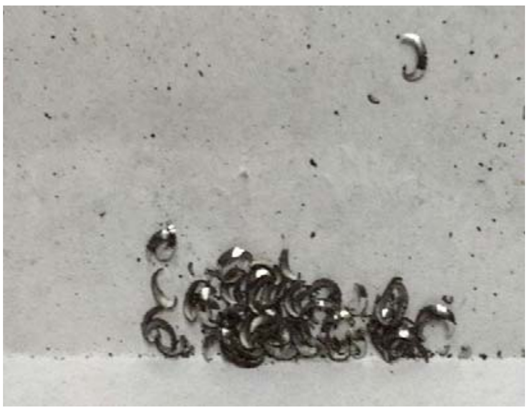

Figure 7. Carbide discontinuous chips

Figure 8. cubic boron nitride discontinuous chip

The discontinuous chips were also seen in case of carbide (figure 7), but in carbide, the thickness was small, and in cubic boron nitride the discontinuous chips(figure 8) observed are of comparatively large thickness. So this shows that carbide is more preferred for roughing operations than cubic boron nitride in the machining of mild steel[9].

Cubic boron nitride is a very hard material which shows very less dependence on heat produced during machining which can be seen in the tool figures comparison done after machining. The reason for this is the making of cubic boron nitride by cryogenic treatment conditions which makes it able to be widely used for machining many materials.

5. Abaqus simulation

The coupling of cutting process of the work-piece and machine tool is done in the software abaqus. The external turning of work-piece is done using the inserts and mesh is analyzed. Other than the mesh and chip analysis, abaqus also provides various failure models with and without damage propagation and element deletion during the chip formation which shows movement of the whole mesh connected by seed nodes in the material movement during the interaction [1] , the observation graphs of which are shown in tables 3,4,5. The material flow is seen along with the mesh nodes in the interaction in abaqus by which frictional contact and shear stress transmitted at work-piece can be analyzed. The element deletion used in the simulation is due to the shear failure of the work-piece during the interaction. Both compression and shear forces act on the work-piece and tool during the interaction [1].

For the 3d process simulation, the constants of the solid and homogeneous elements i.e. mild steel and different insert materials were entered and results were seen. The constants entered were the Johnson cook damage factors of elements i.e. d1,d2,d3 and strain rate , the mass density, young's modulus, Poisson's ratio and the Johnson cook hardening coefficients for the elements i.e. a,b,n. The displacement/rotation step was selected for the simulation under a dynamic and explicit procedure. The amplitude for the step time was entered as 0.001 frequency for 1 amplitude. The boundary condition and velocities were provided to the interaction. Then finally the mesh was created and seeding was done to submit the interaction for job simulation. The analysis are shown in figure 9,10 and 11.

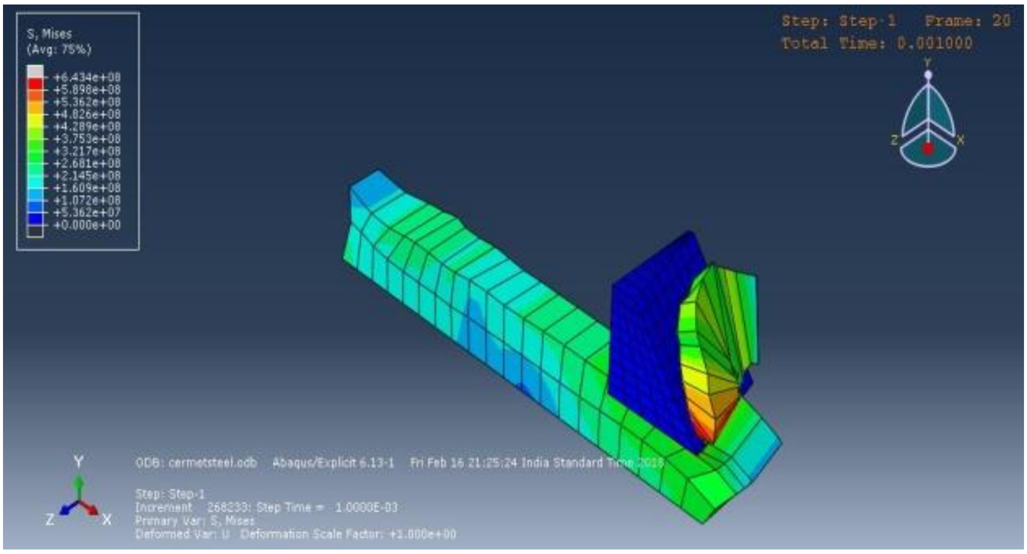

Figure 9. Chip formation in abaqus of carbide.

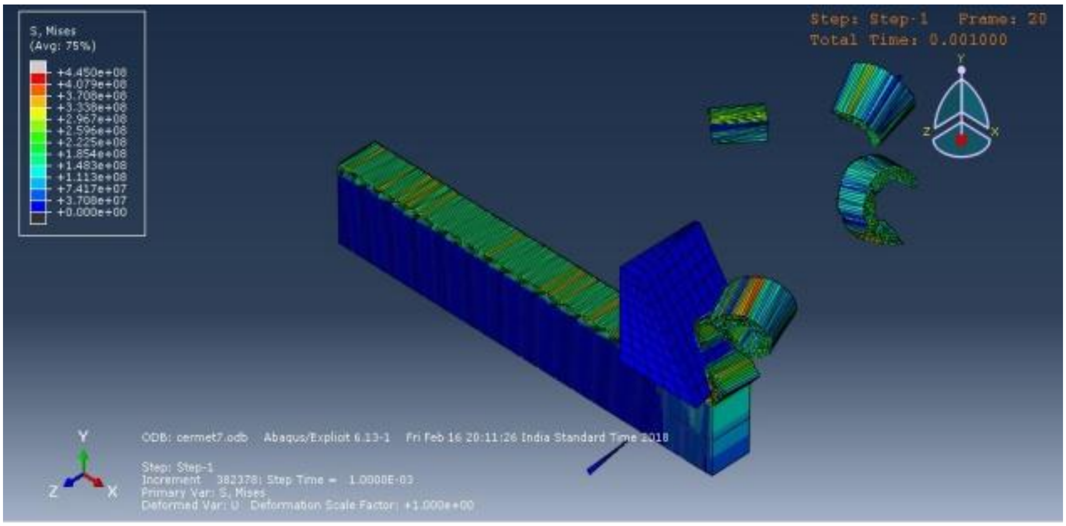

Figure 10. Chip formation in abaqus of cermet.

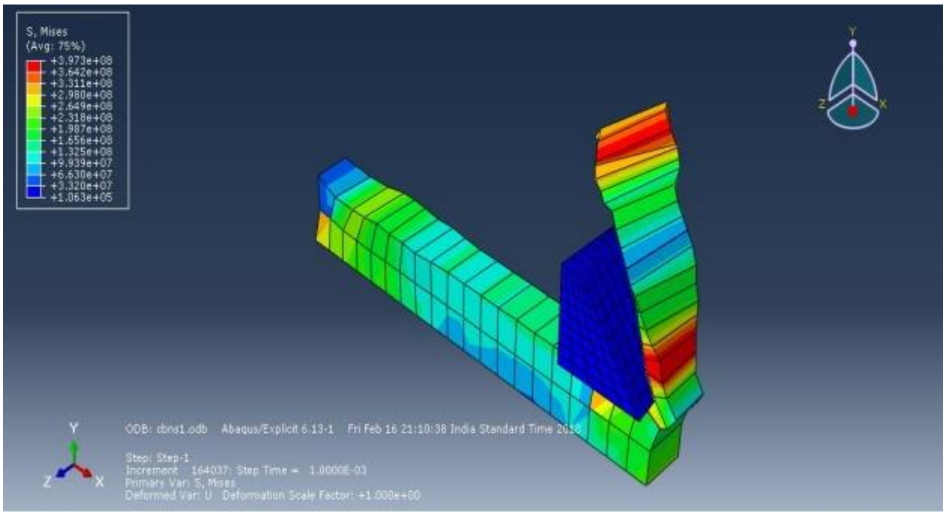

Figure 11. Chip formation in abaqus of cubic boron nitride

6. Surface finish testing

The Surface finish testing was done using ACTEE software and respective instrument having 2 µm diamond stylus. The instrument was set at a sampling length of 4mm and cut off of 0.8mm. The observations show that cermet provides the best surface finish followed by carbide and then cubic boron nitride[10].

Table 3. Surface roughness data

Material	Average roughness (µm)	Mean square roughness (µm)	Peak roughness (µm)
Carbide	1.3315	1.5799	5.8014
Cermet	0.8682	1.0629	4.2008
Cubic boron nitride	3.2480	3.8533	14.8855

There are many different roughness parameters in use, but average roughness is by far the most common, though this is often for historical reasons and not for particular merit, as the early roughness meters could only measure average roughness. The carbide tool provides an average roughness of 1.3315 units, mean square roughness of 1.5799 units, and peak roughness of 5.8014 units.

Similarly, the cermet tool provides an average roughness of 0.0862 units, mean square roughness of 1.0629 units, peak roughness of 4.2008 units, and the cubic boron nitride tool provides an average roughness of 3.2480 units, mean square roughness of 3.8533 units, peak roughness of 14.8855 units.

The cermet tool provides an average roughness of 0.0862 units which is the least among all the cutting tools, this shows that cermet – sintered ceramic provides the best surface finish. While cubic boron nitride provides the most surface roughness, so least surface finish, so cubic boron nitride can be used for roughing purposes.

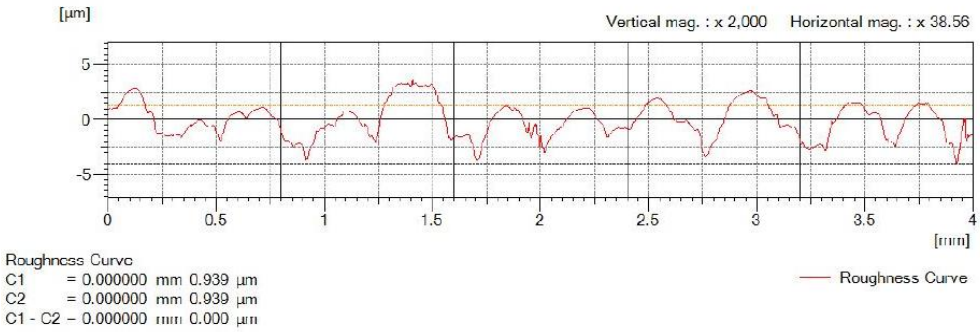

Figure 12. Surface roughness: mild steel: carbide

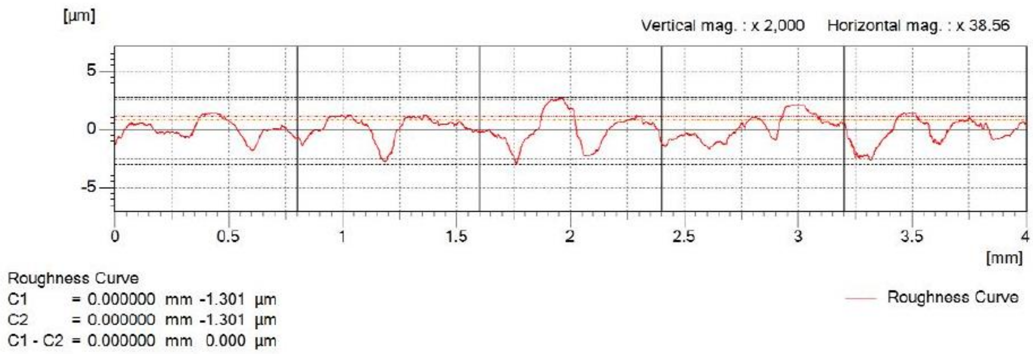

Figure 13. Surface roughness: mild steel: cermet

The figure 12 shows the waviness of the surface and the texture analysis of the carbide tool machined mild steel material. The carbide tool provides an average roughness of 1.3315 units, mean square roughness of 1.5799 units, and peak roughness of 5.8014 units.

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The figure 13 shows the waviness of the surface and the texture analysis of the cermet tool machined mild steel material. The cermet tool provides an average roughness of 0.0862 units, mean square roughness of 1.0629 units, and peak roughness of 4.2008 units

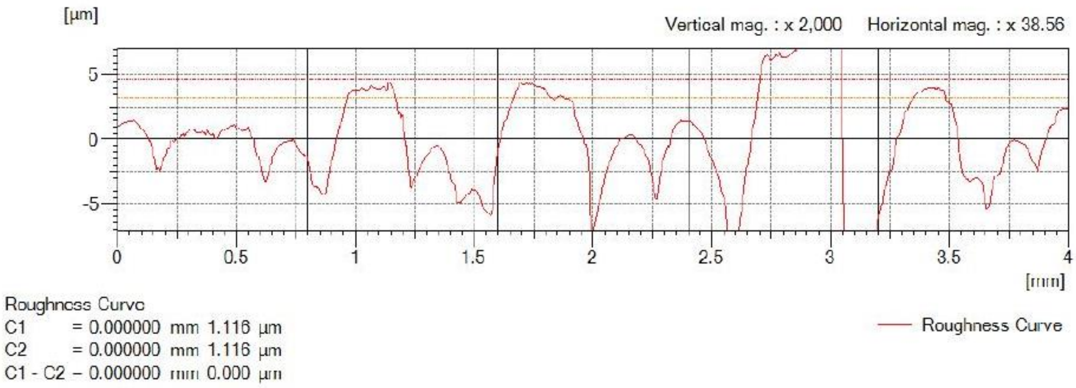

Figure 14. Surface roughness: mild steel: cubic boron nitride

The figure 14 shows the waviness of the surface and the texture analysis of the cubic boron nitride tool machined mild steel material. The cubic boron nitride tool provides an average roughness of 3.2480 units, mean square roughness of 3.8533 units, and peak roughness of 14.8855 units.

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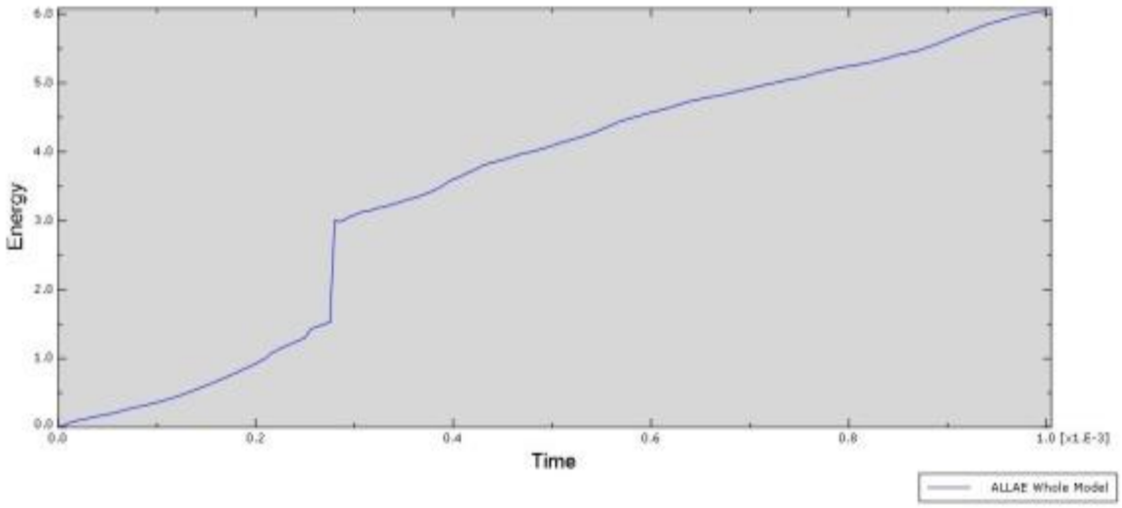
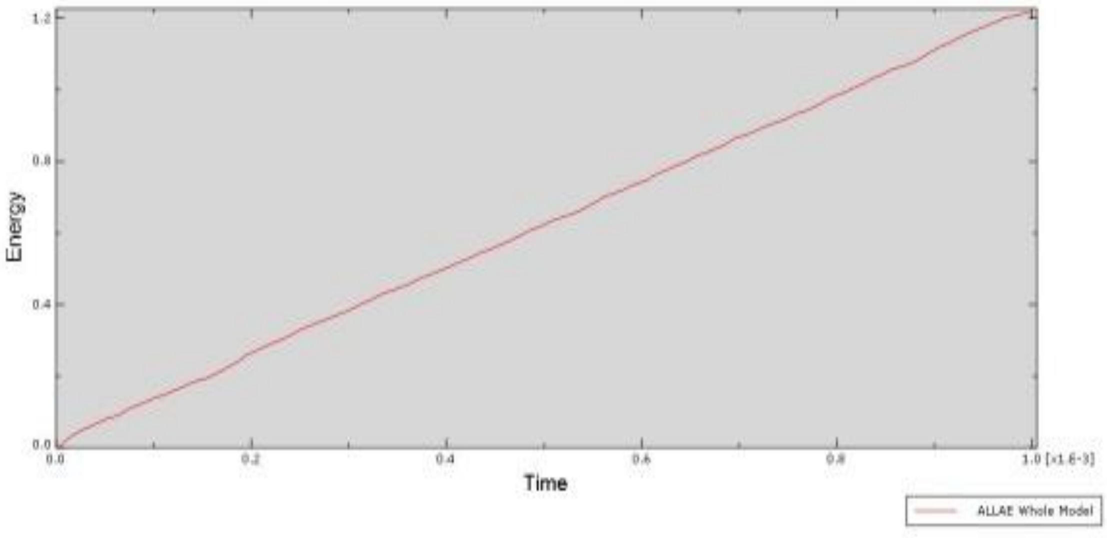
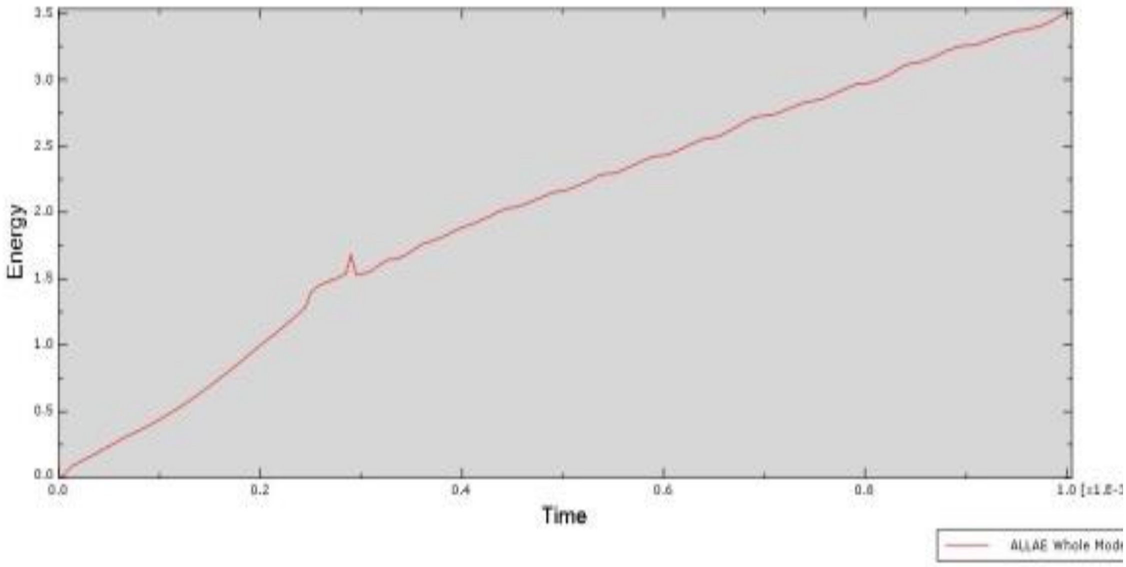
7. Research discussion

Table 4. Strain energy in tool during machining of mild steel.

	Strain energy in whole operation
Carbide	
Cermet	

Cubic boron nitride



The time vs. energy graph shown in table 4 shows the variation of strain energy during the machining of mild steel using various cutting tools. Strain energy is the energy stored in the material required for operation. During plastic deformation of material, most of this energy is converted into heat. The more the strain energy, more heat will be formed, resulting in more tool wear. From the graphs, strain energy at the end of the operations is 6 units in carbide, 1.2 units in cermet and 3.5 units in cubic boron nitride. So cermet has the least strain energy for the same time and same operation, so it is best for finishing of mild steel.

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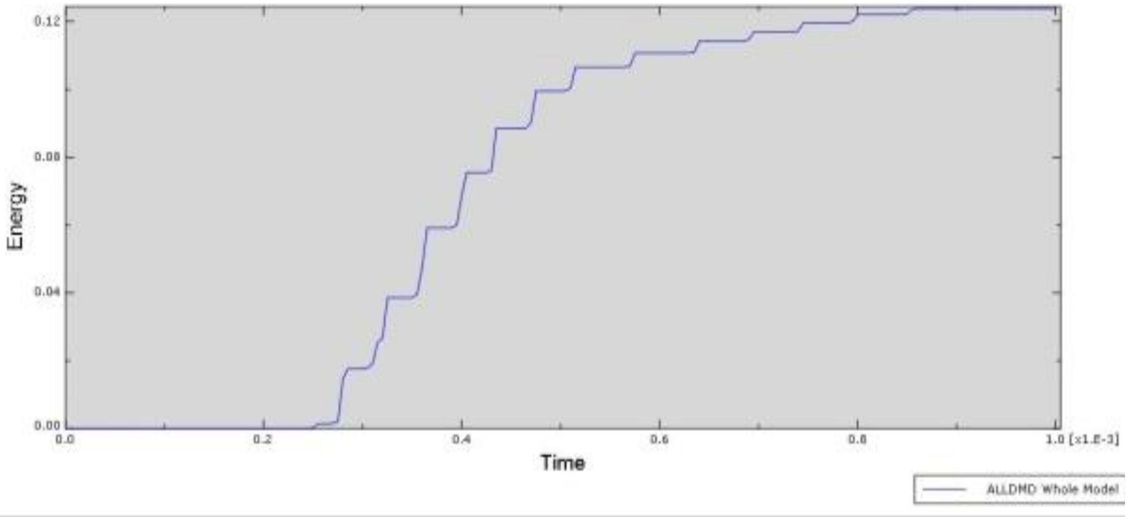
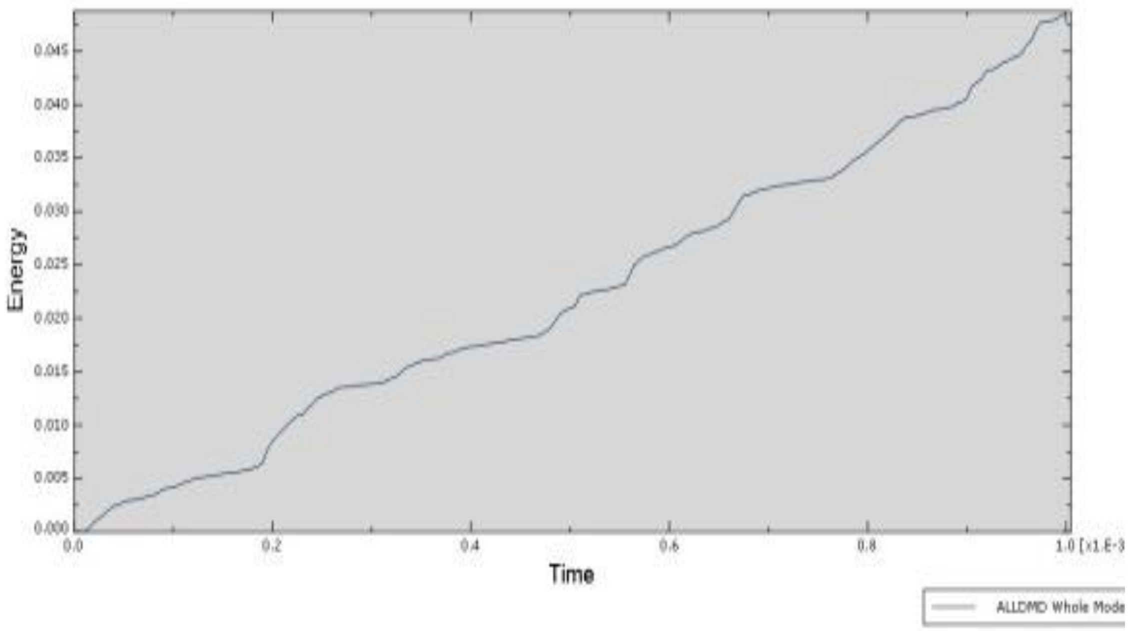
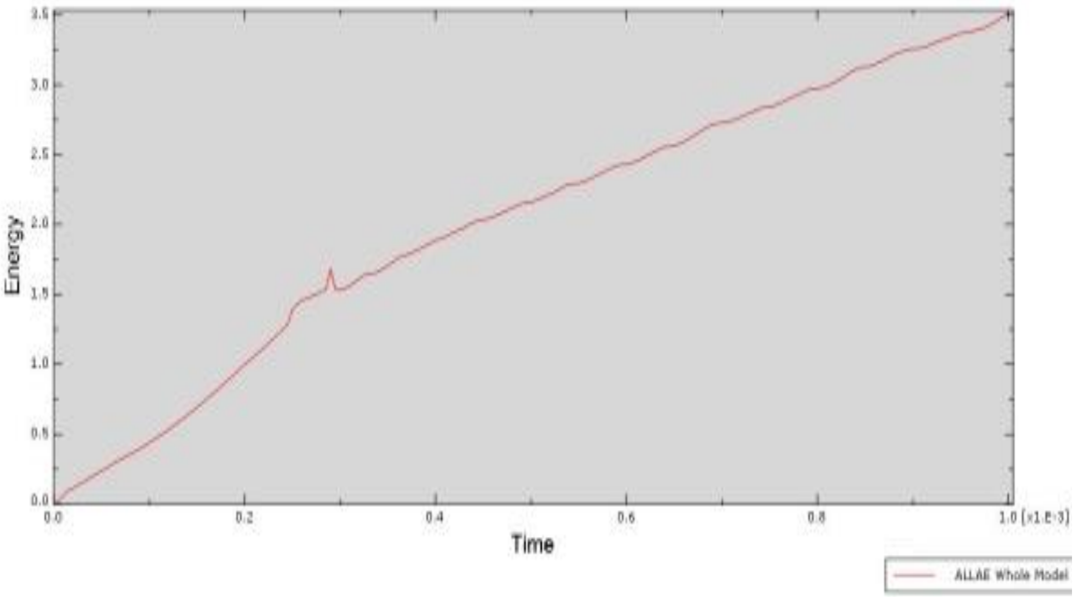
Table 5. Damage dissipation in tool during machining of mild steel.

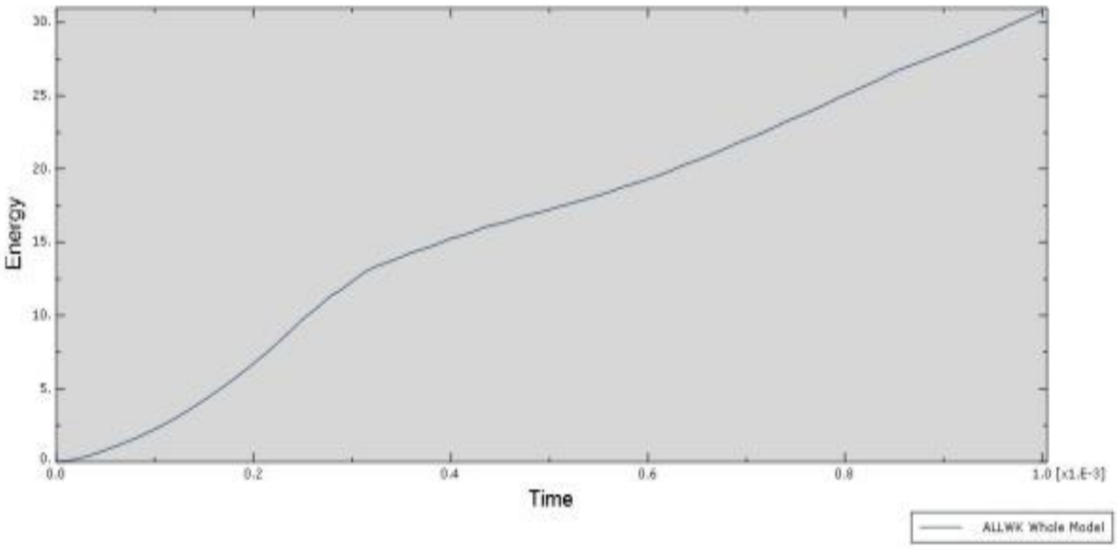
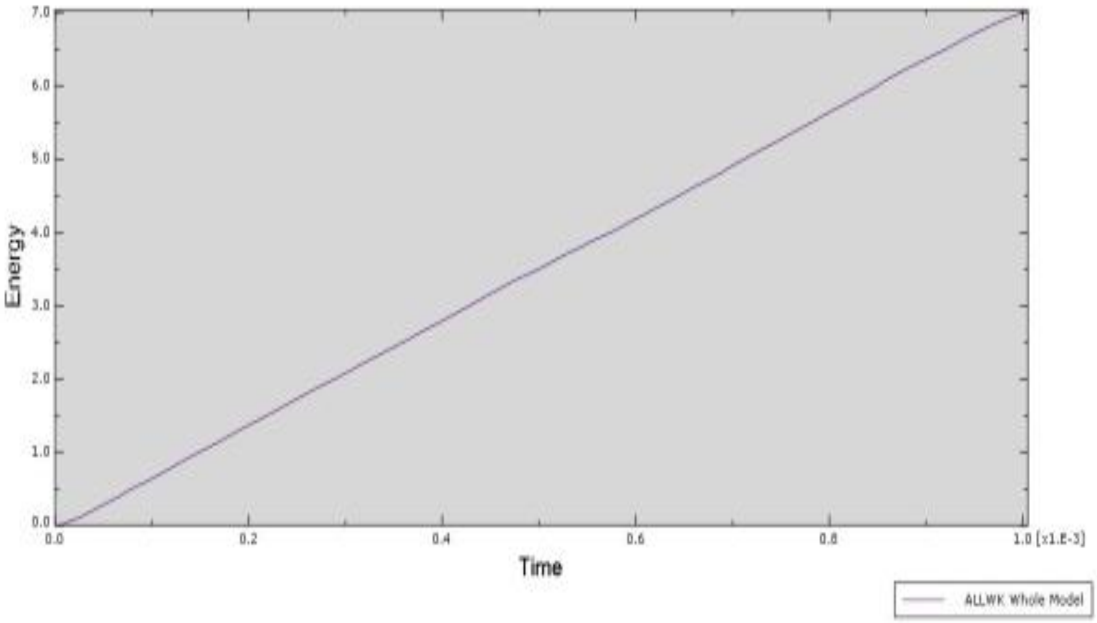
	Damage dissipation
Carbid e	
Cermet	

Cubic boron nitride



The time vs. energy graph in table 5 shows the damage dissipation during the machining of mild steel. The damage dissipation is basically the dissipated amount of energy inside the tool. The more energy dissipated, more will be the chances of wear and failure. From the graphs, energy dissipated at the end of the operations is 0.12 units in carbide, 0.045 units in cermet and 0.2 units in cubic boron nitride. So cermet has the least chances of failure as it has least energy dissipated while providing the best surface finish.

Table 6. Work done by tool during machining of mild steel.

	Work done by tool
Carbide	
Cermet	

Cubic boron nitride

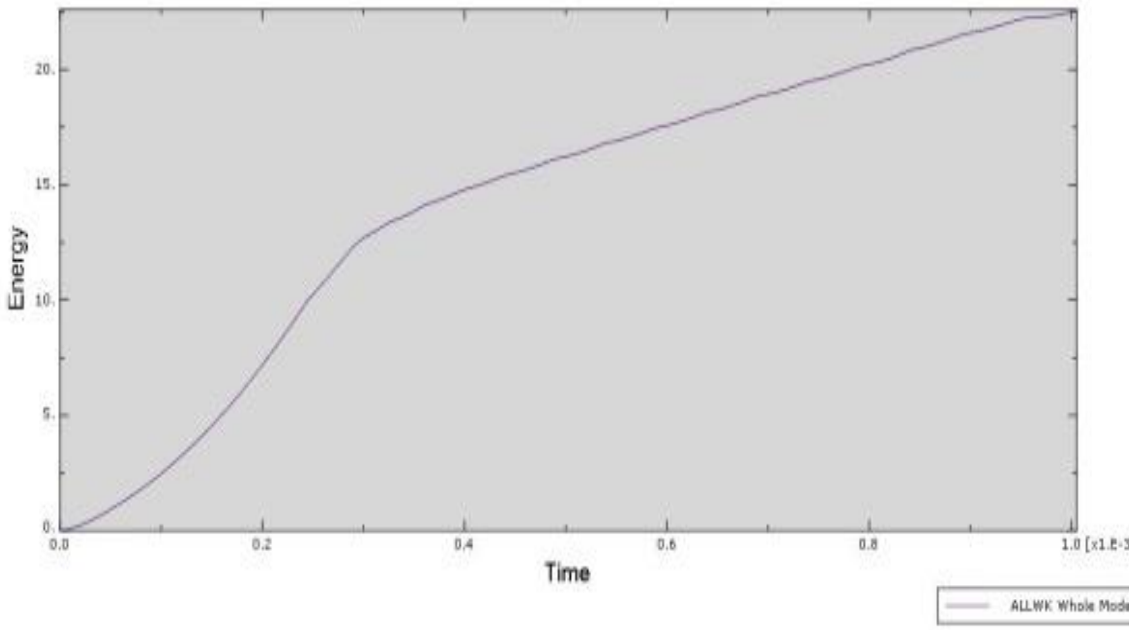


Table 6 shows the total work done by the tool during the whole external turning of mild steel. From the graphs Work done is 30 units in carbide, 25 units in cbn and 7 units in cermet. Cermet provided best surface finish, on mild steel work-piece than other tools for external turning taking least amount of energy to do work.

8. Conclusion

The results of the machining of the mild steel are shown; the chip formed is shown and coupled with the chip formed with the abaqus simulation. The type of chip produced in different interactions in machining is shown and the optimum spindle, feed rate and depth of cut are analyzed.

For roughing purposes, tools with smooth small size discontinuous chips are preferred, so the carbide is preferred over the cubic boron nitride [5]. The suitable small sized discontinuous chips are obtained at a lower depth of cut of 0.5mm and feed rate 0.15mm/rev.[8] For the finishing and grinding purposes on mild steel, the tool with the fine small thickness short chips which provide a better surface finish, this is obtained at a depth of cut of 0.5mm and feed rate 0.25mm/rev. For cubic boron nitride, the optimum feed rate is 0.15mm/rev at a depth of cut of 0.25mm. [9]

The coupled abaqus simulations also show the formation of chips according to the property constants. The chip breaking can be seen the pictures shown. Further simulations will be performed to see the process including variations.

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