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FEM modeling of coated tools to study the influence of coating thickness

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The aim of this paper is to study the performance of coated tools in machining with multilayer coatings. The coatings are made usually by using PVD or CVD techniques, coating material should be in such a way that it should make a very strong bond with the base material. In this paper FEM model is developed by considering workpiece as AISI 1045 and tool as three layered ($TiC/Al_2O_3/TiN$) coated tungsten carbide. Deform 2D software is used to simulate model. initially the model is simulated at different feed rate to observe the temperature distributions and then results are compared with the experimental values to validate the model. After ensuring the accuracy of the developed model, performance of tungsten carbide coated tool is studied by using this model. The influence of coating thickness is observed at same machining conditions. Cutting forces, cutting temperature and effective strains are measured for all the combination of coatings selected in this study

***Keywords*:** Vibration Assisted Turning; Ti6Al4V alloy; Finite Element Modelling; ANOVA; Optimization.

1. Introduction

In conventional machining processes, to get good dimensional accuracies and surface finish are difficult. Available alternatives to get the quality of product in the machining technologies are cutting fluids, nanofluids, Minimum Quantity Lubrication (MQL), solid lubricates, coating technologies etc. Coating technology has become more significant in machining technologies, most of the coated tools are produced by Chemical Vapor Deposition (CVD) or Physical Vapor Deposition (PVD). CVD is the most dominating process and it has advanced its technology from single layered to multilayered coatings.

Selection of coating material deepens on application of cutting tool, coatings should have high hot hardness, good bonding with base material. Interfacial bonding layers can be used to achieve good bonding between the coating and substrate and thin inert nature of coating on the top of wear resistance layer to decrease the corrosion of the cutting tools. The first coating was a single layer of TiC of 10 to 12 microns of thickness produced by CVD, during the deposition some part of carbon was taken from the hard substrate there by having imbalance of carbon at the interface coating and substrate and it causes brittle nature and leads to the chipping of cutting edge, next development was TiN which prevents decarburizing of hard metal surface, but the coating is in gold color and it does not adhere much well to hard substrate, TiN is good diffusion barrier than TiC but TiC has good abrasion resistance. And to get the thermal insulation ceramic coatings came into the picture which includes Al_2O_3, Cr_2O_3 etc.

Abhay Bhatt et.al [1], observed that the three layered ($TiCN/Al_20_3/TiN$) CVD coating exhibits the highest wear resistance at high speeds and low feeds. P.C. Jindal et.al [2], investigated performance of TiN, TiCN and TiAlN PVD coatings at high and low speed machining. W. Grzesik[3] . It was observed that the difference in the measured values of the interface temperatures when comparing single and three-layered coatings reached 290°C.

W. Grzesik et.al [4] observed that in three layered coated tools the maximum differences of chip- tool interface temperature was about 10%. Jeong Suk Kim et.al [5], investigated that hard coatings can improve the performance of cutting tools in a high-speed machining. Attanasio et.al [6,7] were the first to transfer the described methodology to three-dimensional tool wear analysis simulating the tool wear for the machining of AISI 1045 with uncoated WC tools. M. Binder et.al [8] reported tool wear simulation by using Usui model for coated (TiAlN) and uncoated tools.

In the present work, model is simulated by using Deform 2D by considering workpiece as AISI 1045 and tool as three layered ($TiC/Al_2O_3/TiN$) coated (WC) tungsten carbide. Initially the model is simulated at different feed rate to observe the temperature distributions and then comparing with the literature for the validation of the model. Once the validation is done, by changing the coating thickness, few combinations are made, and model is simulated at all the combination by keeping all input parameters constant. From each combination cutting forces in both the directions, cutting temperature and effective strains are measured, among all the combination one is selected such that all the output parameters are optimized.

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2. Modelling and simulation

In this work, model is simulated by turning of AISI 1045 steel using three layered CVD coated ($TiC/Al_2O_3/TiN$) tungsten carbide tool. DEFORM 2D software is used for finite element analysis. DEFORM 2D software is based on an implicit Lagrangian computational approach. At initial stage of simulation, the process parameters for work piece and tool insert have to be defined. During simulation an initial temperature of 20^0C, shear friction factor of 0.5, heat transfer coefficient of 45 N/s/mm/C and no coolant is used. Thickness of the coating layers has been defined as 6 microns for TiC, 3 microns for Al_2O_3 and 1 micron for TiN, A three layered CVD coated (TiC, Al_2O_3 and TiN) and tungsten carbide tool is used. Here, the work piece is considered as plastic material whereas the tool insert is treated as rigid material. In the simulation process, total length for work piece has been taken as 3 mm and length of cut has been taken as 2mm.

The physical and mechanical properties of AISI 1045 steel are: density 7800 modulus of elasticity 205 Gpa, specific heat capacity 420 J/kg0C, thermal conductivity 38 W/m/K, melting. Fig 1 to 3 shows mesh generation of tool, work piece and positioning of the before simulation started.

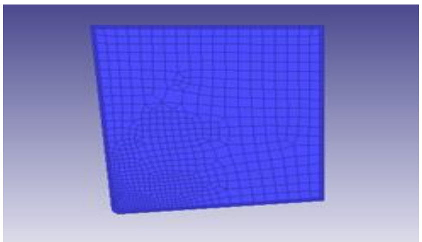


Fig. 1. Coated tool with mesh

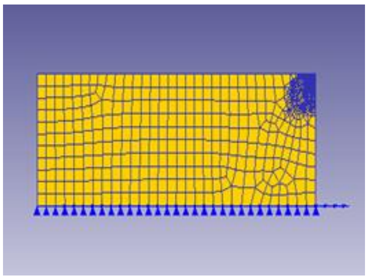


Fig. 2. Work piece with mesh generation before simulation simulation

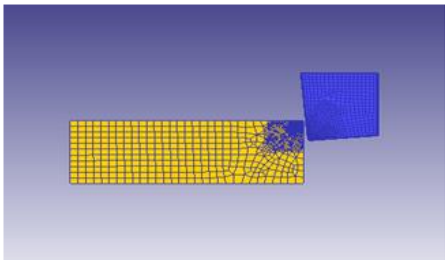


Fig. 3. Positioning of the workpiece and tool before simulation.

2. 1. Material Modelling

Johnson–cook model is suitable for modelling material because high strain, strain rate, strain hardening, and non-linear material properties are involved in turning process. The material model is given in Eq. (1)

$$\sigma = (A + B\epsilon^{n})\left(1 + Cln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)[1 - (\frac{T-T_r}{T_m-T_r})^{m}] \qquad (1)$$

The first is elastic-plastic term and it represents strain hardening. The second one is viscosity term and it shows that flow stress of material increases when material is exposed to high strain rates. The last one is temperature softening term. A, B, C, n and m are material constants that are found by material tests. T is instantaneous temperature, Tr is room temperature and T_m is melting temperature of a given material. Johnson-Cook material model assumes that flow stress is affected by strain, strain rate and temperature independently. The model constants for tool and workpiece are shown in Table 1 and Table 2.

Table 1. Johnson-Cook model constants for AISI 1045[8]

A[MPA]	B[MPA]	C(-)	n(-)	m(-)	T_m(K)	Strain rate(S^{-1})
546	487	0.25	0.027	0.631	1733	0.631

Table 2. Johnson-Cook model constants for WC coated tool

A[MPA]	B[MPA]	C(-)	n(-)	m(-)	T_m(K)	Strain rate
1200	1100	0.35	0.475	1	2800	1

Table 3. Cutting conditions and tool geometry used in simulation

Tool rake angle (^{0})	5
Tool clearance angle (^{0})	-5
Cutting edge radius(microns)	0.33
Length of cut (mm)	2
Cutting speed(m/min)	103.2

2. 2. Multilayer coatings

Although the single layer coating is useful for many engineering applications, there are some applications where the properties of single layer material is not enough. One way to overcome this problem is to use a multilayer coating that combines the properties of several material layers. Each layer has chosen for to solve a problem in the application. It consists of as many as eight layers of thickness with in the 10microns or less

3. Results and Discussions

In this, the workpiece AISI1045 steel and three-layered WC coated tool have been selected to perform simulation. The aim is to evaluate the influence of various output parameters i.e. cutting forces in X and Y directions, effective strain, temperature by varying coating thicknesses ($TiC/Al_2O_3/TiN$).

3.1 Effects of coatings

The main aim of the coatings is to provide high hardness, wear resistance and the chemical stability. Besides coatings are helpful to increase the tool life by 2 to 3 times by decreasing the wear rate in high speed machining of steel and cast. Tool life is increased in a large amount by coating with one layer of TiN produced by CVD process, because single layer of TiN acts as a diffusion barrierTiC provides good surface roughness and reduction of Built Up Edge (BUE) when compared with the uncoated ones. The inert nature of Al2O3 and TiC will reduce the cratering and has high resistance to abrasion and hence low flank wear. Al2O3 also acts as a thermal barrier because of very low thermal conductivity.

3.2 Validation of the model

The model is simulated by considering different feed rates at constant cutting speed (220m/min) and depth of cut (1mm). The multilayered ($TiC/Al_2O_3/TiN$) coated tool having coated thicknesses of 5 microns each. The interface temperature is observed at all feed rates and compared with the experimental values[3] shown in the table 4.1. When the model is simulated at feed rates of 0.05, 0.1, 0.15, 0.2 and 0.25mm/rev. The temperatures are observed to be 551^0C,602^0C, 625^0C, 639^0C and 720^0C respectively. The values which are observed to be compared by the experimental values and error is tabulated.

Table 4. comparison between Simulation and Experimental values. (cutting speed= 220m/min, depth of cut = 1mm)

S. No	Feed rates (mm/rev)	Temperatuer observed in simulaton(^{0}C)	Temperature in literature(^{0}C)	Error(%) (^{0}C)
1	0.05	551	560	1.6
2	0.1	602	630	4
3	0.15	625	640	2.38
4	0.2	639	670	4.68
5	0.25	731	720	1.25

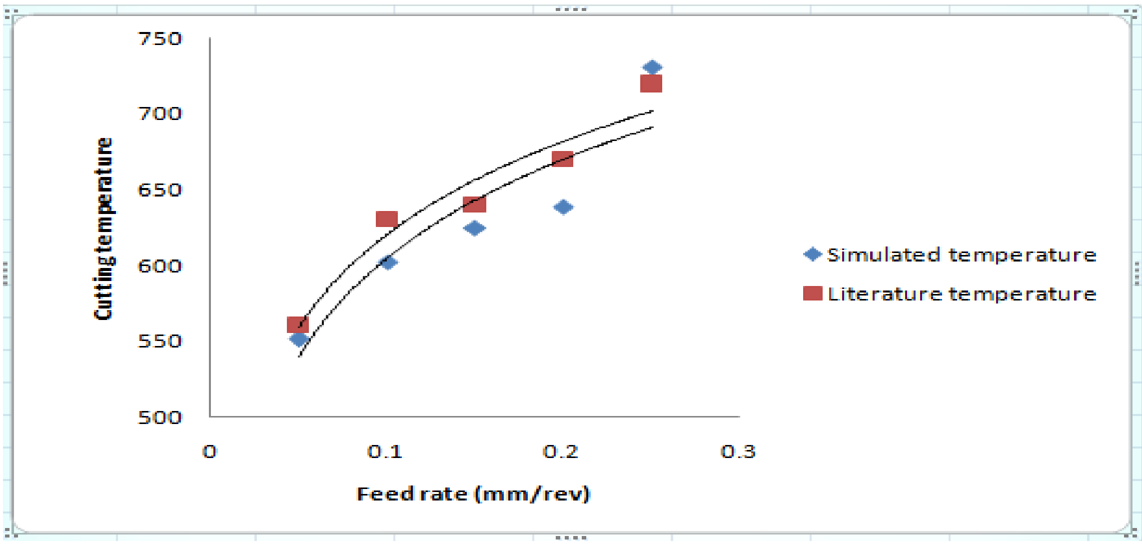


Fig. 4. temperature at different feed rates

Figure 4 shows the temperature variation at different feed rates. Temperature obtained from the simulation is compared with experimental values for the validation. As the feed rate increases temperature increases.

3.3 Study on multilayer coatings performance in orthogonal cutting

The model is simulated by considering process parameters i.e. cutting speed of 103.2m/min, depth of cut of 0.3mm and feed rate is 0.16mm/rev by varying coating layer thicknesses of TiC, Al_2O_3 and TiN. The aim of the present work is to find the best combination of thicknesses of coated materials where the output parameters i.e. cutting force, temperature, effective strains are observed. Out of all the combinations one is selected in such a way that where output parameters are optimized. All the input parameters and combination of coating layer thicknesses are shown in the table 5

Table 5. Combination of layer thicknesses used in the simulation (v= 103.m/min, f= 0.12mm/rev and depth of cut = 0.3mm)

S.no	TiC(microns)	Al_2O_3(microns)	TiN(microns)
1	6	3	1
2	5	3	1
3	7	3	1
4	6	4	1
5	6	2	1
6	6	3	2
7	6	3	3

3.4 Cutting force

The figure 5 shows variation of cutting forces in both direction X and Y when the coating thicknesses of TiC is 6 microns, Al2O3 is 3microns and TiN is 1 micron at constant cutting conditions. The average cutting forces at the tool- chip interaction in X and Y directions from the simulation are observed to be 642N and 222N.

Cutting forces always reduce by using coatings on cutting tool when compared with the uncoated cutting tool. For TiC, as the coating thickness varies from 5 to 7, the forces in x and y direction changed as shown in the figure 6, as the coating thickness varies cutting force increased from 618N to 642N and then again increased to 649N,consequently the force in y the direction force is constant at thicknesses 5 and 6 microns and then increased to 224N, it is observed that the force in Y-direction did not affect much because the main cutting action is carried out in the X direction. As the thickness of coating increases the sharpness of cutting edge gets reduced, so it requires more force to cut the material.

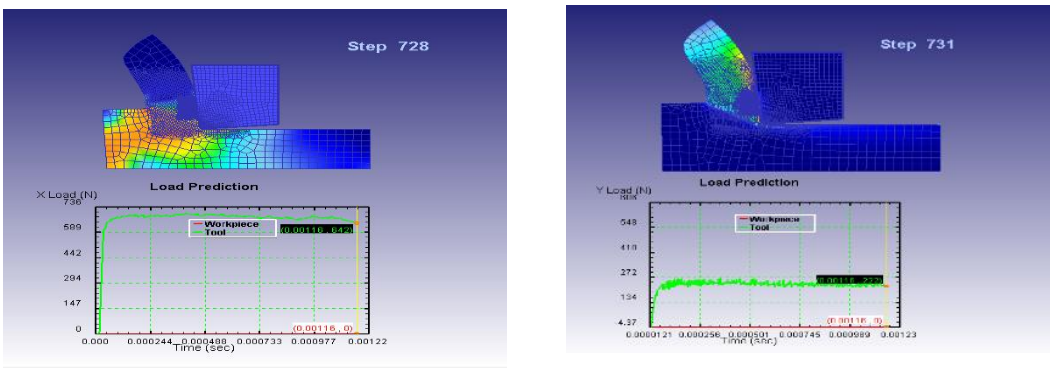


Fig. 5. Cutting forces in X and Y directions at TiC = 6μm, Al_2O_3 = 3μm and TiN =1μm

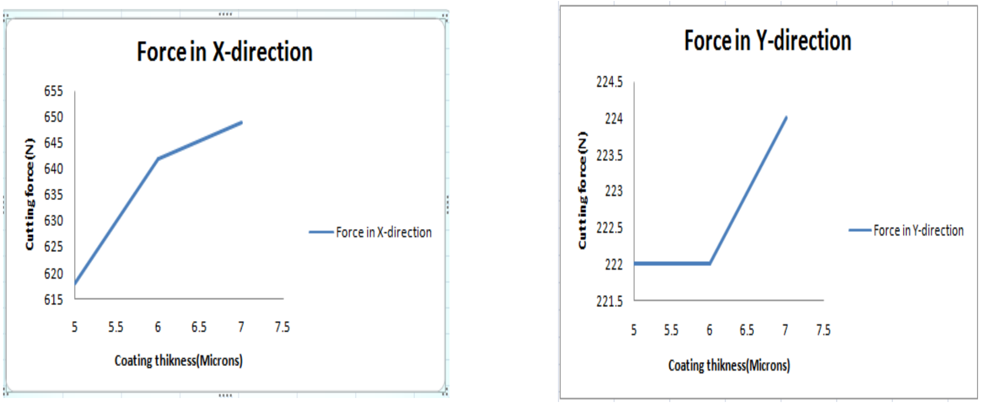


Fig. 6. Cutting forces in X and Y directions when TiC varied from 5 to 7

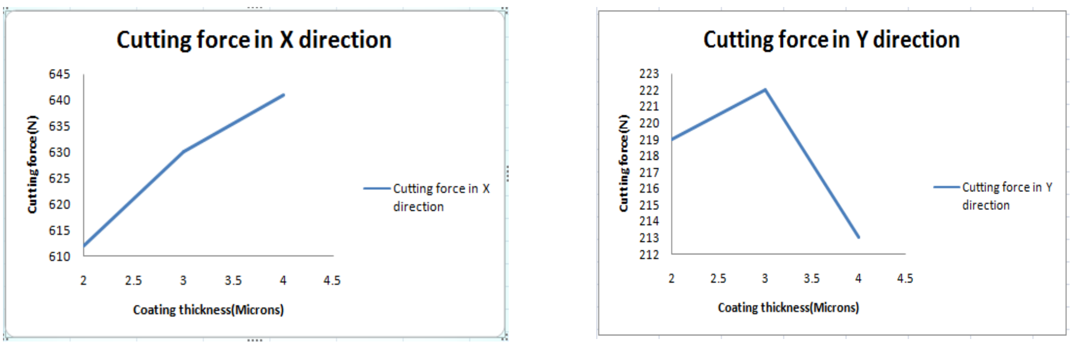
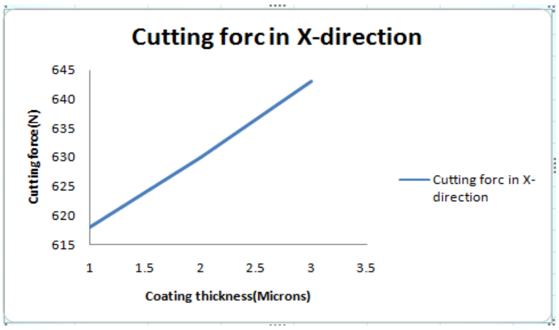


Fig. 7. Cutting forces in X and Y directions when Al_2O_3 varied from 2 to 4

For Al_2O_3, as the coating thickness varies from 2 to 4 the forces in x and y direction changed as shown in the figure below, as the coating thickness varies, cutting force increased from 612N to 630 N and again increased from 630N to 641N,consequently the force in y the direction force is increased from 219N to 222N and then decreased to 222N to 213N. Al_2O_3 does not have much effect on cutting forces, when many alternating layers of two materials are deposited can lead to improvement in performance over a mixed coating even if two materials do not have specific functional requirements in the intended application

As TiN provides low friction, the values of cutting forces reduce if TiN coating is used. For TiN, as the coating thickness varies from 1 to 3 the forces in x and y direction changed as shown in the figure 8, as the coating thickness varies, cutting force increased from 618 N to 630N and then again increased from 603N to 643N,consequently the force in y the direction force increased from 222N to 223N and then reduced from 223N to 220N.



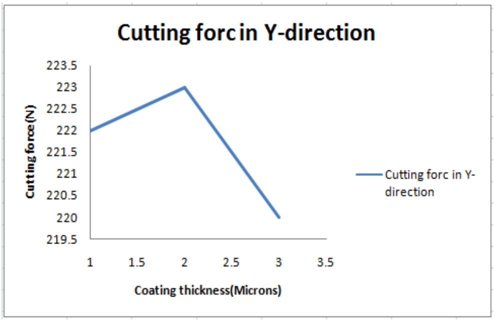


Fig. 8 Cutting forces in X and Y direction when TiN varied from 1 to 3

3.5 Cutting temperature

The figure 9 shows temperature distribution when coated layer thicknesses of TiC is 6 microns, Al_2O_3 is 3 microns and TiN is 1 micron. Model is simulated at constant cutting conditions; the temperature is observed at the tool chip interface is around 641^0C.

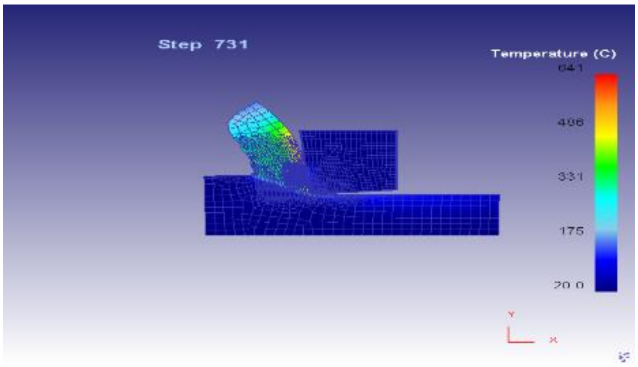


Fig. 9. Temperature distribution at TiC = 6µm, Al_20_3 = 3µm and TiN = 1µm thicknesses

The graph 10 indicates variation of temperature when the thickness of TiC varies from 5 to 7, as the coating thickness varied from 5 to 6 microns cutting temperature reduced from 6480C to 6410C and then if thickness varied from 6 to 7 microns, then the temperature reduced from 6410C to 6400C. Because of being inert nature of TiC, as the coating thickness increases temperature reduces gradually. Thickening of coating materials do not allow the temperature through it. So it is observed that temperature is reduced.

The figure 11 indicates variation of temperature when the thickness of Al2O3 varies from 2 to 4 microns, as the coating thickness varied from 2 to 4 microns cutting temperature reduced from 6420C to 6410C and then again decreased from 6410C to 6350C. As the thickness of Al_2O_3 increases temperature reduces, because Al_2O_3 has low thermal conductivity and it does not allow heat produced in machining through it. So ultimately temperature reduced.

The figure 12 indicates variation of temperature when the thickness of TiN varies from 1 to 3 microns, as the coating thickness varied from 1 to 3 microns cutting temperature reduced from 641^0C to 640^0C and then again reduced 640^0C to 639^0C As coating thickness of TiN increases temperature reduced, it mainly works as a diffusion barrier and helps in reduction the friction there by temperature is reduced.

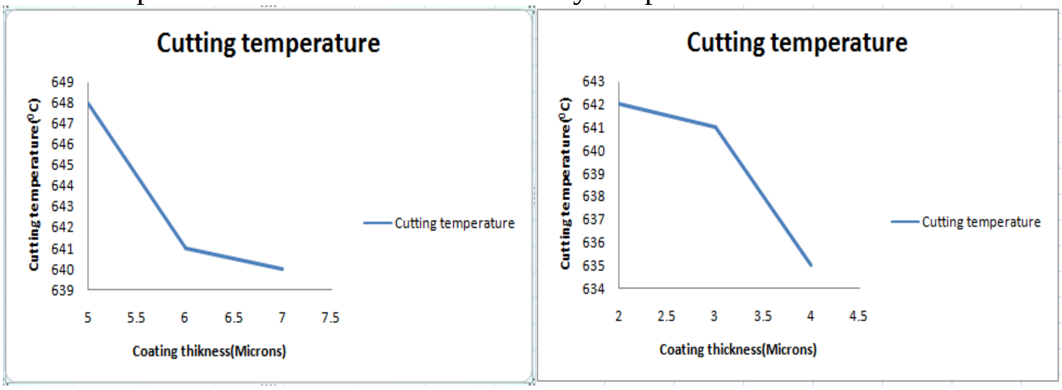


Fig. 10 &11**.** Variation of temperature when the thickness of TiC varied from 5 to 7 and Variation of temperature when the thickness of Al_2O_3 varied from 2 to 4. thickness of TiC varied from 5 to 7.

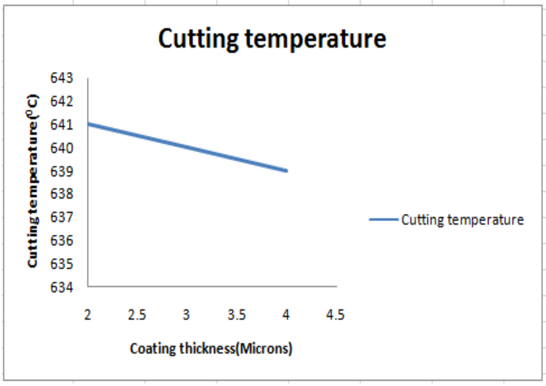
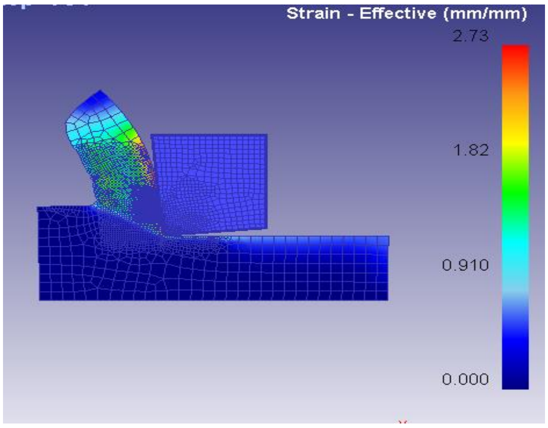


Fig. 11. Variation of temperature when the thickness of TiN varied from 1 to 3

3.6 Cutting force

The figure 13 shows Effective strain when coated layer thicknesses of Ti C is 6 microns, Al_2O_3 is 3 microns and TiN is 1 micron. Model is simulated at constant condition. effective strain is observed to be 2.73.



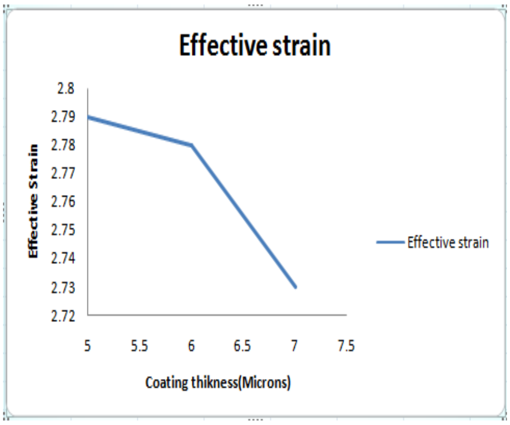


Fig. 12. Effective strain at TiC = 6µm, Al_20_3 3µm and TiN = 1µm thicknesses

Fig. 13. Variation of effective strain when the thickness of TiC changes from 5 to 7

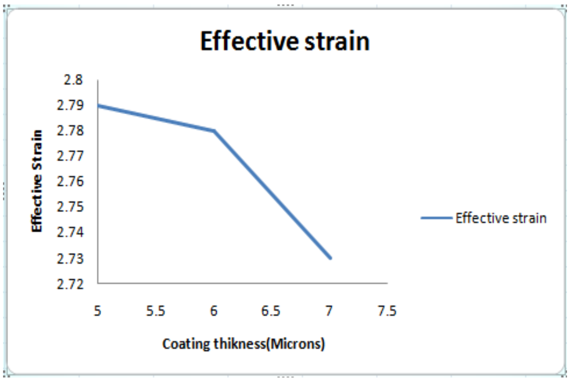
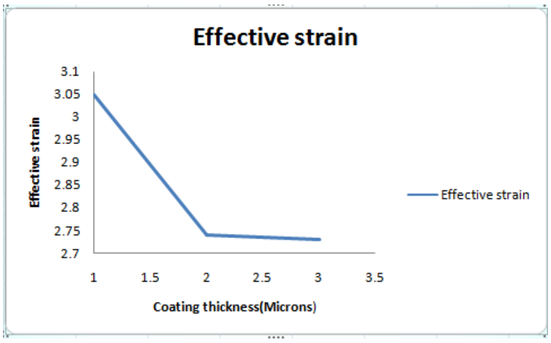


Fig. 14. Variation of effective strain when the thickness of TiC changes from 5 to 7

The figure 14 indicates variation of Effective strain when the thickness of TiC varies from 5 to 7, as the coating thickness varied from 5 to 6 microns, effective strain is reduced from 2.79 to 2.78 and then if thickness varied from 6 to 7 microns, then the again is decreased from 2.78 to 2.74.

The figure 15 indicates variation of Effective strain when the thickness of Al_2O_3 varies from 1 to 3, as the coating thickness varied from 1 to 2 microns, then the effective strain is decreased from 3.05 to 2.74 and then constant from 2 to 3 microns. Cutting temperature is related to the effective strain. As the plastic deformation increases, temperature increases which in turn leads to the increase in effective strain.

The figure 16 indicates variation of Effective strain when the thickness of TiN varies from 1 to 3, as the coating thickness varied from 1 to 3 microns, then the effective strain is increased from 2.74 to 2.77.



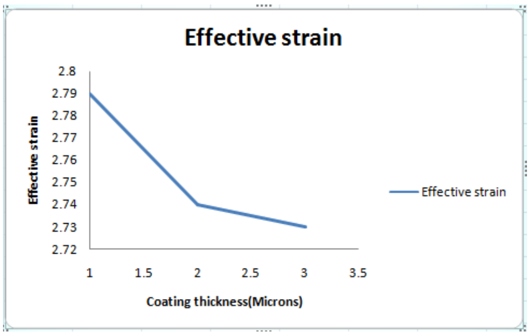


Fig. 15.& 17 Variation of effective strain whenthe thickness of Al_2O_3 changes from 2 to 4 microns and Variation of effective strain when the thickness of TiN Changes from 1 to 3 microns

Table 6 shows the results for all the combination of coating thicknesses. After ensuring the accuracy of the developed model, performance of tungsten carbide coated tool is studied by using this model. The influence of coating thickness is observed at same machining conditions. Cutting forces, cutting temperature and effective strains are measured for all the combination of coatings selected in this study. Based on the results, it observed that forces are optimized when TiC = 6microns, and Al2O3 = 2microns and TiN = 1micron. Favourable results for temperature and effective strain is at TiC = 6microns, and Al2O3 = 4 microns and TiN = 1micron.

Table 6. Results for all the combinations of coating thicknesses

S.No	TiC (μ)	Al_2O_3 (μ)	TiN (μ)	F_x(N)	F_y(N)	Temp (^{0}C)	Effectve strain
1	6	3	1	642	222	641	2.78
2	5	3	1	618	222	648	2.79
3	7	3	1	649	224	640	2.73
4	6	4	1	641	213	635	2.73
5	6	2	1	612	219	642	3.05
6	6	3	2	630	223	640	2.77
7	6	3	3	643	220	639	2.74

4 Conclusion

In the present work, the Workpiece AISI 1045 steel is subjected to cutting operation by using the software Deform 2D with coated tungsten carbide as a a cutting tool, in this model is simulated to get temperature distribution at different feed rates by keeping other parameters constant after that, model is compared with literature for the validation of the model. The model is simulated by considering process parameters i.e. cutting speed of 103.2m/min, depth of cut of 0.3mm and feed rate is 0.16mm/rev by varying coating layer thicknesses of TiC, Al_2O_3 and TiN. The aim of the present work is to find the best combination of thicknesses of coated materials where the output parameters like cutting force, temperature and effective strains are observed

After ensuring the accuracy of the developed model, performance of tungsten carbide coated tool is studied by using this model. The influence of coating thickness is observed at same machining conditions. Cutting forces, cutting temperature and effective strains are measured for all the combination of coatings selected in this study. Based on the results, it observed that cutting forces are optimized when TiC = 6microns, and Al_2O_3 = 2microns and TiN = 1micron. Favourable results for temperature and effective strain is at TiC = 6microns, and Al_2O_3 = 4 microns and TiN = 1micron.

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