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A FEM Analysis of Residual Stresses in Metal Cutting Process

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Abstract: In present scenario residual stresses in different metal cutting operation is very interesting topic for researchers and much research is going on different areas of it. Surface integrity is very essential parameter during metal cutting process. In this paper many aspects of surface integrity are discussed and residual stresses are predicted with finite element model. A comparison is made between the experimental value and predicted value by finite element model. The effect of coated and uncoated tool at different cutting parameter is discussed. In recent days more work is going on residual stress with Ti–6Al–4V titanium alloy for its critical application.
Keyword: Residual Stresses, Ti-6Al-4V Titanium alloy, Finite element method

I. INTRODUCTION

Surface integrity is very important parameter of machined components, as per applications of that product. This is the parameter which decides component performance, reliability and life cycle of the component. It describes the nature of surface condition of component after machining [1-2-3-4]. One of the major aspects of surface integrity is surface texture (surface topography characteristics) which includes surface roughness and other surface topographic features. The second aspect is related to subsurface layer characteristic, which includes microstructure transformation (plastic deformation, phase change, recrystalization etc) and mechanical properties (residual stress, hardness etc). In many applications such as in aeronautic, nuclear, automotive and medical high quality and reliability is requested for that a great surface integrity level is required [5-6-7-8-9].

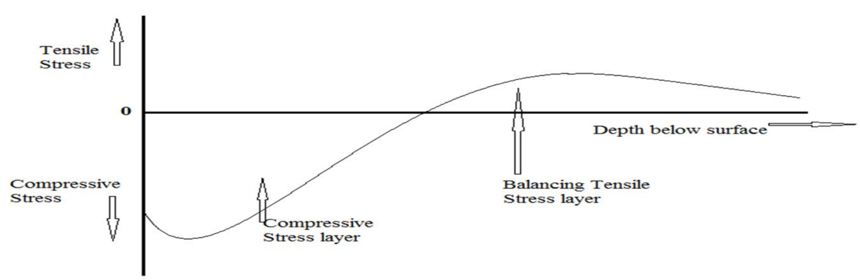

Fig 1: Variation of residual stress with depth

Residual stress is very relevant factor to evaluate quality of machined component keeping high reliability in mind [10]. Fatigue life and corrosion resistance property are strongly affected by residual stress. Due to their importance analysis of residual stress becomes a working subject [11-12]. Due to large amount of plastic deformation in metal cutting processes (like in turning process) very high strains are generated which introduces stress on the surface either of tensile nature or compressive nature, this induced stress is actually Residual stress. Generally tensile residual stress is undesirable due to adverse effect in various factors like strength, fatigue life, corrosion; wear resistance etc., whereas compressive residual stress has beneficial effect on these properties. Compressive residual stress increases the performance of component and life because it allows more service tensile stress and also delays the crack initiation and propagation. At the surface of the machined part residual stress has highly tensile nature but with increase in depth compressive nature of stress is increases, becomes maximum (around 50 µm) and then levels. The parameters by which residual stress are most affected are cutting speed, feed rate and depth of cut. With increase in cutting speed residual tensile stress drooped while when there is increase in feed rate it results slight increment in surface tensile stress as well as depth of compressive stress layer is also increases. At lower cutting speed with higher feed results less compressive peak [13-14-15-16-17].

II. LITERATURE REVIEW

The best surface roughness is achieved at a low feed rate combined with a high cutting speed and also with a large tool nose radius when cutting speed is high and feed rate low [19]. Feed rate is the most influencing factor followed by nose radius and cutting speed on the surface roughness [20]. A larger tool nose radius provides less fluctuation in surface roughness when operating under different depths of cut conditions. Tool vibration increases with feed rate and depth of cut, and long tool reduces tool vibration. A short tool length deteriorates surface roughness when combined with a small tool nose radius [21]. An optimal value of cutting speed may be calculated for each value of roughness and for each insert. For ceramic inserts, the optimal value of cutting speed is equal to 7463 m/min. The optimal cutting speed is independent of roughness [22]. The insert radius and feed rate are the main parameters among the three controllable factors (insert radius, feed rate and depth of cut) that influence the surface roughness in metal cutting. In metal cutting, use of greater insert radius, low feed rate and low depth of cut are recommended to obtain better surface roughness [23].

For longer tool lives dry turning cannot be used for high values of depth of cut. When using cutting fluid, a tough tool material is required and in dry cutting, the tool has to have high hot hardness. On the flank face the cause of wear was abrasion and adhesion, and on the rake face, the causes were diffusion, abrasion and attrition [24]. Mr. L.J. Xie, J. Schmidt had done FEA analysis in two steps, first step complete modeling of chip formation from initial chip formation, chip growth, to steady-state chip formation can be used in continuous chip formation analysis. In second step heat analysis is done. High density of mesh is localized at the produced surface, which is opposite to flank face, and coarse mesh formed on the outside surface of chip with the chip growing. This causes contact noise and makes some nodes on the tool face lose contact with the chip, which affects the cutting process variables, such as heat flux, temperature, and contact pressure seriously [25].

Chip shrinkage factor can be considered as a measure of the material strain by compression during cutting process. The greatest differences are in the chips obtained when higher feeds are applied, which increases the peak-valley height by increasing the cutting speed. Dry cutting cannot be used for high values of depth of cut, in order to obtain long Tool life. For dry turning tool should have high hot hardness [26].

The residual stresses are much higher at the transversal or cutting direction than at longitudinal or feed direction. High-pressure jet induced a much deeper compress residual stress under similar cutting condition. High compress residual stress resulted on the titanium alloy for roughing [27]. High-pressure water-jet assisted machining of titanium alloys is beneficial because it reduces shear forces in the secondary cutting zone along the tool/chip interface, reduces the cutting force and introduces compressive residual stress in the finished work-piece. This leads a better surface integrity and consequently improves the properties of work metals [28]. Residual stress profile is tensile near the surface, then highly compressive at 50µm and then leveling out with increasing depth by 200µm below the surface. With increase in cutting speed residual tensile stress drooped while increasing feed results slight increment in surface tensile stress as well as depth of compressive stress layer [29]. Higher residual stresses are induced by coated tools [30]. X-ray diffraction method is used for measuring residual stresses. Low cutting speed residual stresses in circumferential direction exceed the axial residual stresses. The elimination of cutting fluid from a turning process of C45 steel increased the magnitude of residual stresses. At higher cutting speed lower roughness is observed at the surface due to fewer flaws on the surface. At higher cutting speed, lower feed rate and at moderate depth of cut higher compressive residual stress are induced [31].

III. FINITE ELEMENT SIMULATION

The modeling part of metal cutting simulation is very important step to achieve accurate results. In analysis, cutting tool is assumed to be a rigid body. The tool is designed as 4x4x4 mm^3 cubic box having Rake angle as 0^0, clearance angle 6^0 and nose radius 8 µm. For this analysis tool material was selected uncoated tungsten carbide (WC/Co) as tool material. Thermal and mechanical properties of tool material are given in Table 1.

Table 1: Thermal and mechanical properties of WC/Co [12]

Elastic Modulus, E (MPA)	Poisson's Ratio	Thermal Expansion (1/ºC)	Thermal Conductivity (N/sec/ºC)	Heat Capacity (N/mm^2 ºC)
560000	0.26	$4.7x10^{-6}$	55	2.075

After modeling the tool the second aspect is to model workpiece. Workpiece is designed as a cuboid with dimension 20x4x4 mm^3. For the analysis purpose, Ti-6-Al-4-V is selected as work piece material. With the help of partition tool the workpiece is partitioned is done in two different sections for meshing purpose. In small section fine meshing is done to achieve better result in simulation, and in big section coarse meshing is done for lesser calculation and time required for calculation is also less.
Then the different properties (like density, elasticity, plastic behavior of material, specific heat etc.) of workpiece material are defined in the model. Since in cutting high amount temperature is generated and these properties changes with temperature. Mechanical properties are shown in Table 2, thermal properties are shown in Table 3 and plastic behavior of material is shown in Table 4 & Table 5.

Table 2: Mechanical Properties of material with temperature [32]

Density, ρ Kg/m^3	Modulus of Elasticity, E (GPa)	Temperature, T (^{0}C)
4420	103	25
4410	99	100
4400	94	200
4380	89	300
4370	84	400
4350	80	500
4340	74	600

Table 3: Thermal properties of Ti-6-Al-4-V [32]

Specific heat capacity, c_p (J/kg^{0}C)	Thermal Conductivity, k (W/m^{0}C)	Linear coefficient of thermal expansion, ξ (μ/m^{0}C)	Temperature, T (^{0}C)
532	7	8.7	25
573	8.6	9.5	200
632	11.5	9.9	400
806	14.4	10.3	600

Table 4: Johnson-Cook material constant for Ti-6-Al-4-V [32]

A	B	n	C	m
1000	625	0.55	0.029	0.995

Table 5: Johnson-Cook material damage constant [33]

D_1	D_2	D_3	D_4	D_5
-0.090	0.27	0.48	0.014	3.870

The upper part of the workpiece is having fine mesh, which contains approximate 8000 hex element and the prime area of focus is on this part. Rest of the part is done with coarse mesh for reducing calculation time. Contact properties are then defined in the model, for surface contact surfaces are defined and then friction coefficient is given for that contact. The value of friction coefficient is given as 0.3. Now boundary conditions are defined as workpiece is fixed by imposing boundary conditions and tool is given a velocity with some feed rate. Different results are drawn by changing velocity and feed values. After giving boundary conditions job is defined and run it.

IV. RESULTS AND DISCUSSION

Firstly, job of the present model is defined and being run, after completion of the job predicted simulation results are found, then these predicted results are compared with experimental results available in the literature. Chip formation during metal cutting process is shown below in Figure 2. In the present model residual stresses are predicted in depth direction (σ_{zz}) as per the input conditions are given as cutting velocity and depth of cut which are given in the Table 6.

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Table 6: Comparison of predicted and experimental value

Cutting Speed, V_c (m/min)	Depth of cut (mm)	Residual stress (Experimental) σ_{zz} (MPa)	Residual stress (Predicted) σ_{zz} (MPa)
90	0.1	-356	-309
55	0.1	-571	-599

In previous table the present model is validated by comparing experimental values with predicted values of residual stresses in depth direction at a constant depth of cut and by changing cutting velocity. Now prediction of residual stresses in depth direction as well as in the surface of workpiece is done. Some more values of predicted values are shown in Table 7.

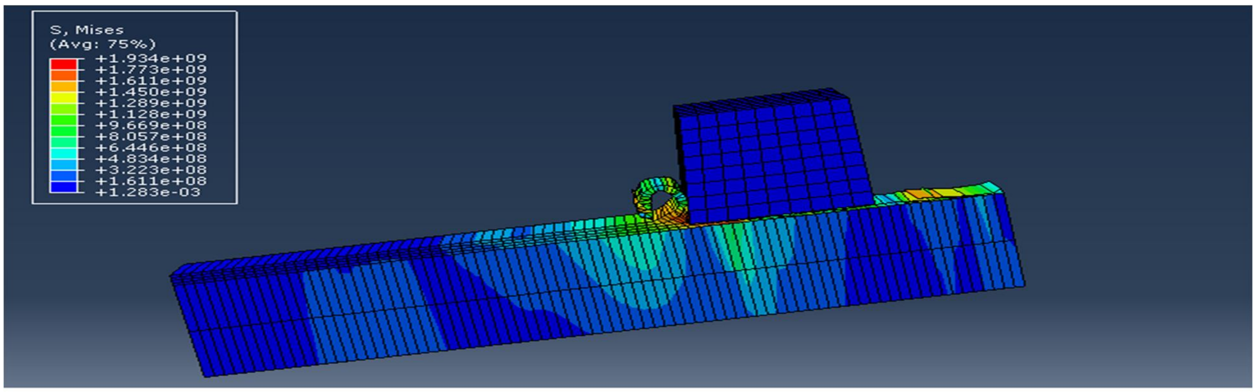

Figure 2: Chip formation during Metal Cutting

Table 7: Predicted values of σ_{zz} and σ_{xx}

Cutting Speed, V_c (m/min)	Depth of cut (mm)	Residual stress in radial direction σ_{zz} (Predicted) (MPa)	Residual stress in circumferential direction σ_{xx} (Predicted) (MPa)
90	0.2	-340	-440
55	0.2	-636	-261

In metal cutting process there exists a region of very high deformation rate and as well as very high stress zone around the round edge of cutting tool. It can also be observed from simulation and experimental value of σ_{zz} that induced residual stress in machining is increases with decrease in the value of cutting velocity with a large difference in the value of residual stress approximate 200 MPa, this shows that cutting velocity significantly affects residual stresses during cutting. Then again it can be observed that from simulated value of σ_{zz} that induced residual stress in machining is increases with increase in the value of depth of but the difference is not very large with the value of residual stress is less than 100 MPa, this shows that depth of cut affects residual stress but not very much. Similarly residual stresses in the surface of workpiece means σ_{xx} have significant changes with velocity, σ_{xx} increases with velocity with a significant difference of approximate 180 MPa, but with increasing depth of cut slight increase occurs in σ_{xx}.

V. CONCLUSION

A thermo-mechanical model dry with continuous chip formation is presented. The developed model is able to predict residual stress distribution. The prediction of machining induced residual stresses in depth direction is main focus of this work and it is effectively carried out, after that the predicted values are compared with the experimental values in the table 5.2 to validate the model. Effect of changing cutting velocity and depth of cut on residual stresses are studied in this work. The value of σ_{zz} in cutting is increases with decrease in the value of cutting velocity with a large difference in the value of residual stress, this shows that cutting velocity significantly affects residual stress. The value of σ_{zz} in cutting is increases with increase in the value of depth of but the difference is not very large with the value of residual stress, this shows that depth of cut affects residual stress but not very much. The value of σ_{xx} in cutting is increases with increase the value of cutting velocity with significant difference, and σ_{xx} is also increases with depth of cut but difference is negligible.

Numerical simulation of turning has proved to be a challenge to existing algorithm and computational tool. Large and localized plastic deformation and complex contact conditions are some of difficulties associated with these classes of problems. In spite of current progress, there is still a need for more research before a modeling practice is established than can predict residual stress with an acceptable degree of accuracy.

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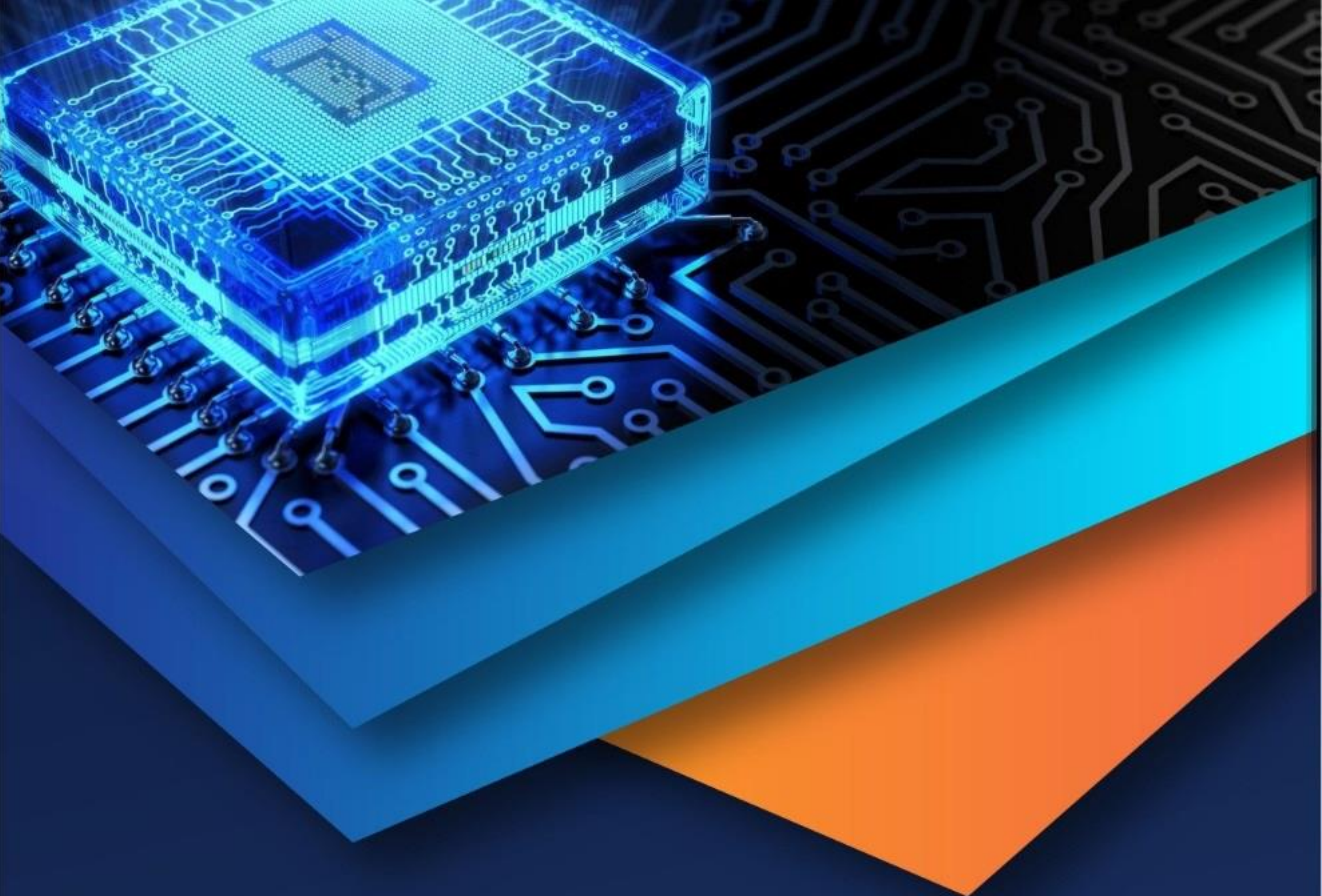

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